UCRL-ID-123465

Hydrogen as a Transportation Fuel: Costs and Benefits

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March 1996

Work performed under the auspices of the Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Figure 1. Elements of a Robust Rationale for Hydrogen Vehicles

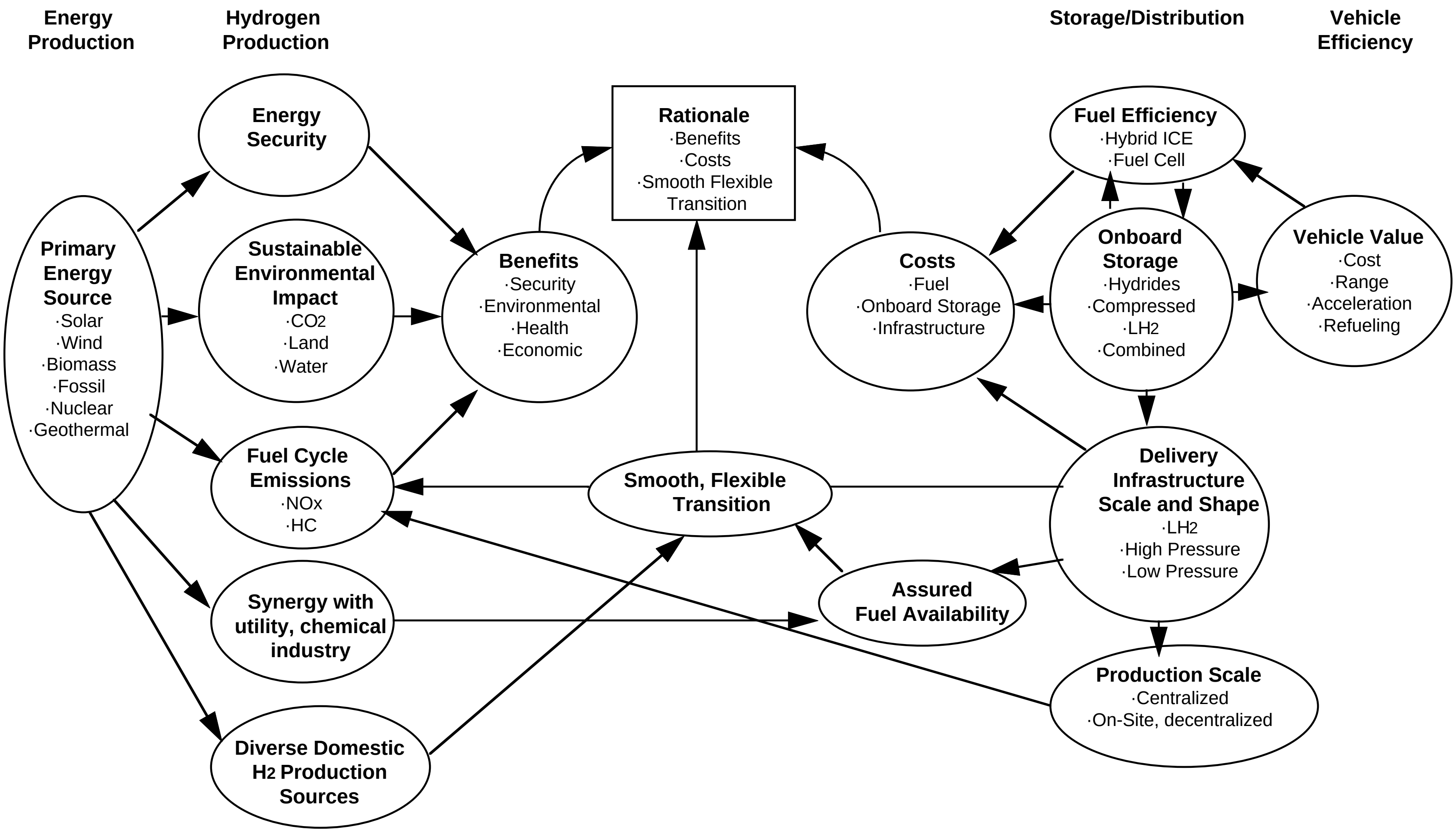

Figure 1. Elements of a Robust Rationale for Hydrogen-Vehicles. Hydrogen competes with today's gasoline vehicles on a rationale composed of a balance of (1) consumer costs, (2) public benefits, and (3) feasibility of a smooth, flexible transition. Hydrogen has many attractive public policy benefits (secure, domestic, sustainable fuel production; clean air; and new markets that enhance the economic efficiency of utilities) that depend mostly upon the primary energy source. But to achieve these benefits, hydrogen vehicles must be successful in the market. Hydrogen vehicles must deliver greater value (cost, range, vehicle life, refueling time, acceleration, etc.) to consumers than other alternative-fuel vehicles. Technical issues and choices of fuel efficiency, onboard storage, delivery infrastructure, and production scale determine to a large extent the value of hydrogen vehicles to consumers. In addition to a high-value vehicle, consumers want assured fuel availability, which at least initially is a major issue involving both technical and business risk aspects of hydrogen infrastructure. Hydrogen is already produced today in industry, and synergies exist with potential fuel suppliers (utilities, chemical industry) who can invest in delivery infrastructure and capture a new fuel market. The development of a reliable hydrogen fuel supply is helped by the diverse domestic sources of hydrogen production and the wide array of possible production, storage, and delivery scales, which allows market entry and decentralization. These provide hydrogen vehicles a unique flexibility and potential for a smooth transition through changes in the mix of primary energy sources used to produce hydrogen fuel in response to market, economic, or regulatory changes.

Figure 2. Conceptual hydrogen powered vehicle

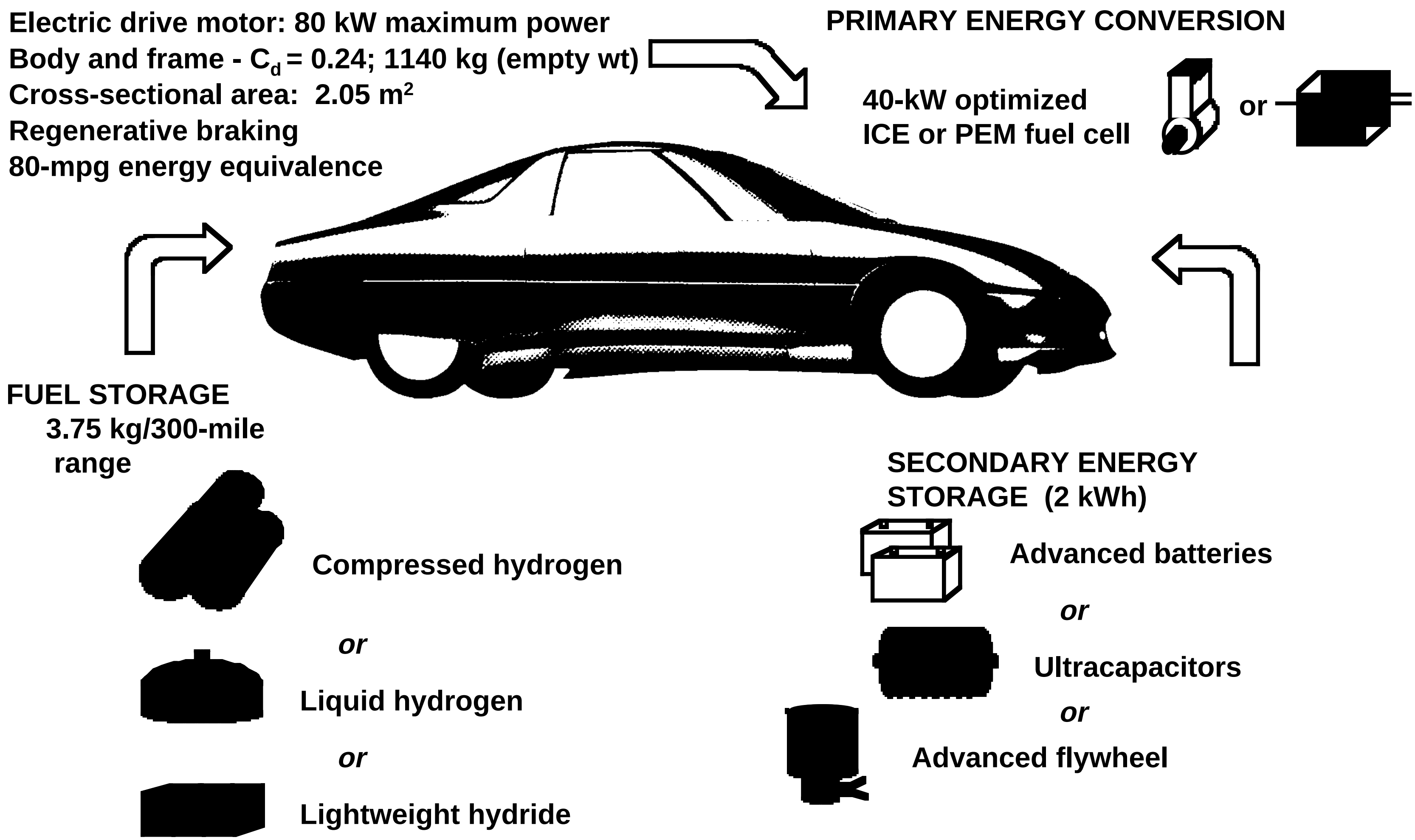

Figure 2. Conceptual design of a hydrogen-powered five-passenger hybrid-electric vehicle that can travel 300 miles using only 3.75 kg of hydrogen fuel, achieving 80-mpg-energy-equivalent mileage. This high fuel efficiency is possible because of a low drag coefficient and high drivetrain efficiency. A small internal combustion engine (or ultimately a fuel cell), optimized for hydrogen, generates electricity at peak efficiency to charge a secondary electrical energy storage device (batteries, a flywheel, or capacitors) that delivers electricity to the electric motor and has sufficient power for peak accelerations and energy recovery from regenerative braking. Hydrogen is stored onboard in a hydride bed, in compressed gas tanks at 5000 psi and room temperature, or cryogenically as a compressed gas (80 K, 3600 psi), or as a liquid (20 K, 5 atm).

Figure 3. Storage systems for 3.75 kg hydrogen (300 mile range at 80 mpg)

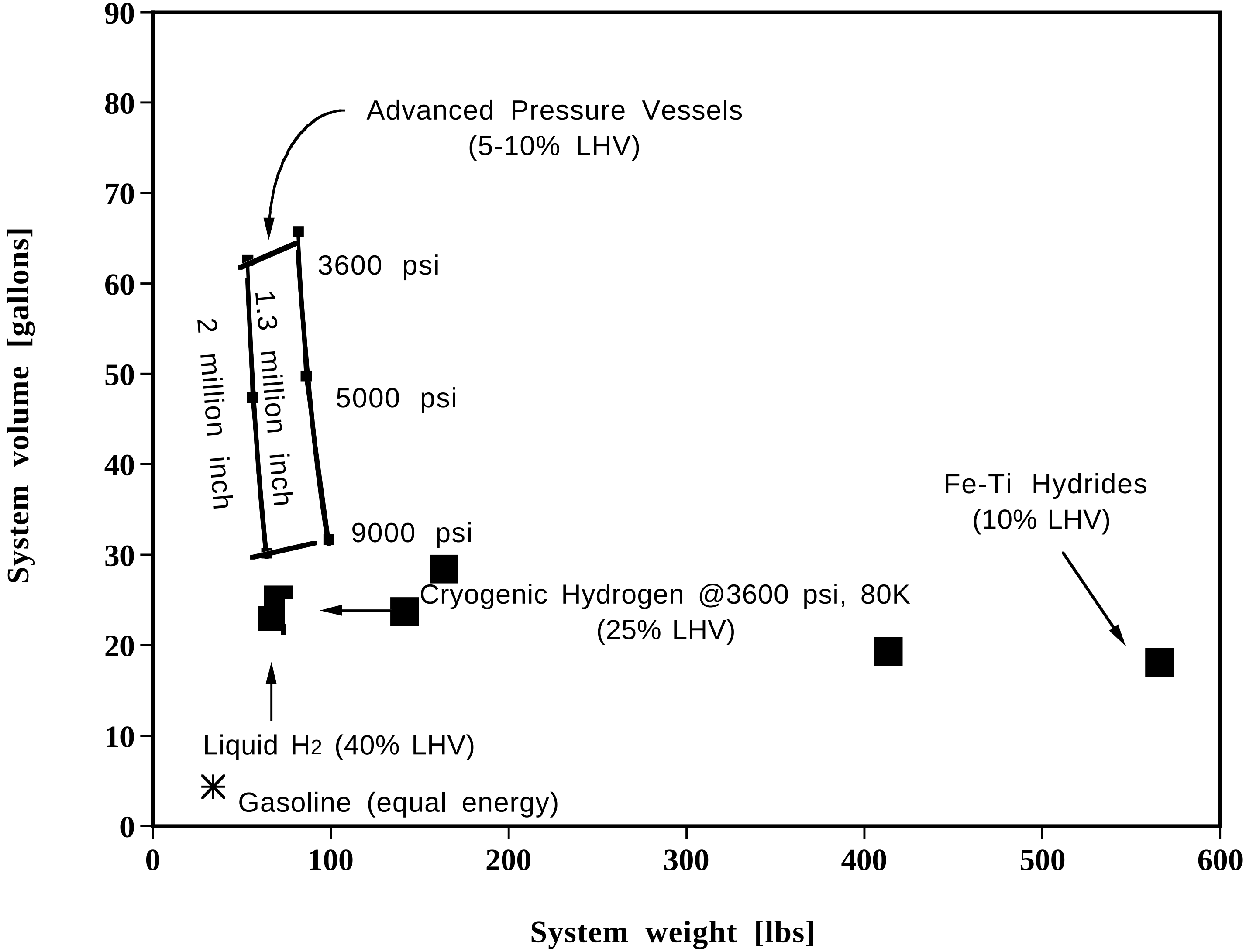

Figure 3. To provide enough fuel for a 300-mile range in an 80-mpg-equivalent hydrogen vehicle, 3.75 kg of hydrogen must be stored onboard. The weight, volume, and storage energy required to store 3.75 kg of H_2 is shown for (1) an Fe-Ti-based hydride (15% energy penalty), (2) carbon-fiber-wrapped aluminum pressure vessels storing hydrogen between 3600 and 9000 psi with a safety factor of 2.25 (5–10% energy penalty), (3) a cryogenic pressure tank storing hydrogen at 3600 psi and 80 K (25% energy penalty), and (4) a low-pressure (1–5 atm) liquid hydrogen tank (40% energy penalty). The system volumes and weights shown are all feasible (although room-temperature compressed gas tanks may require pressures of 5000 psi or above). Compact, lightweight storage technologies require generally large increases in energy requirements.

Figure 4. Hydrogen from natural gas or off-peak electricity is an affordable fuel in 70-100 mpg vehicles

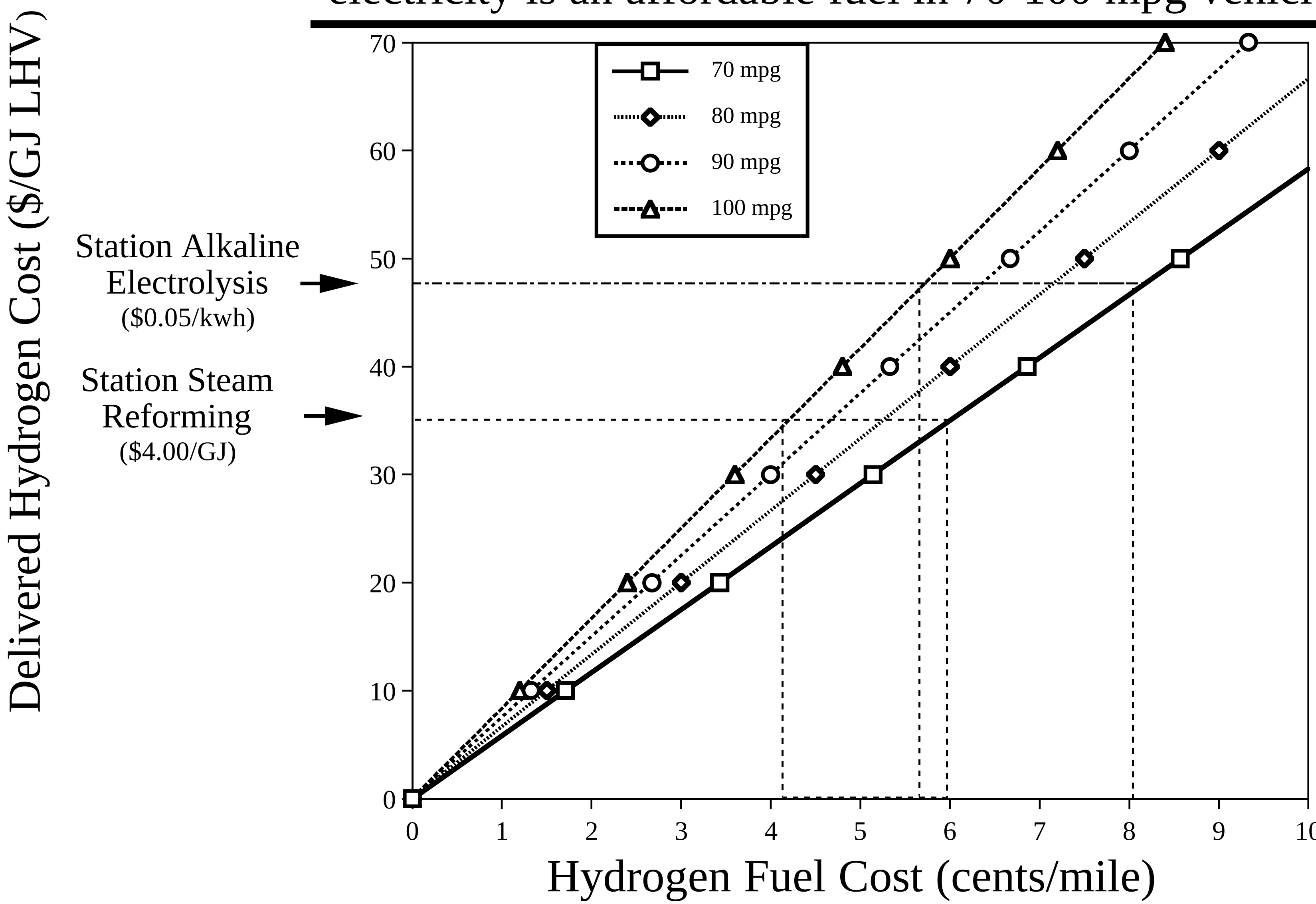

Figure 4. Fuel cost in cents per mile is shown for hydrogen vehicles ranging in fuel efficiency from 70 to 100-mpg gasoline energy equivalent. Hydrogen in filling stations is conservatively estimated to cost at most \$50/GJ (off-peak electrolysis at \$0.05/kWh for electricity). Hydrogen costing \$40/GJ (equivalent to \$5.00/gallon gasoline) corresponds to only \$0.06/mile, comparable to gasoline fueling costs in today's vehicles.

Figure 5. Estimated Costs of Hydrogen Delivery 250 miles by Truck

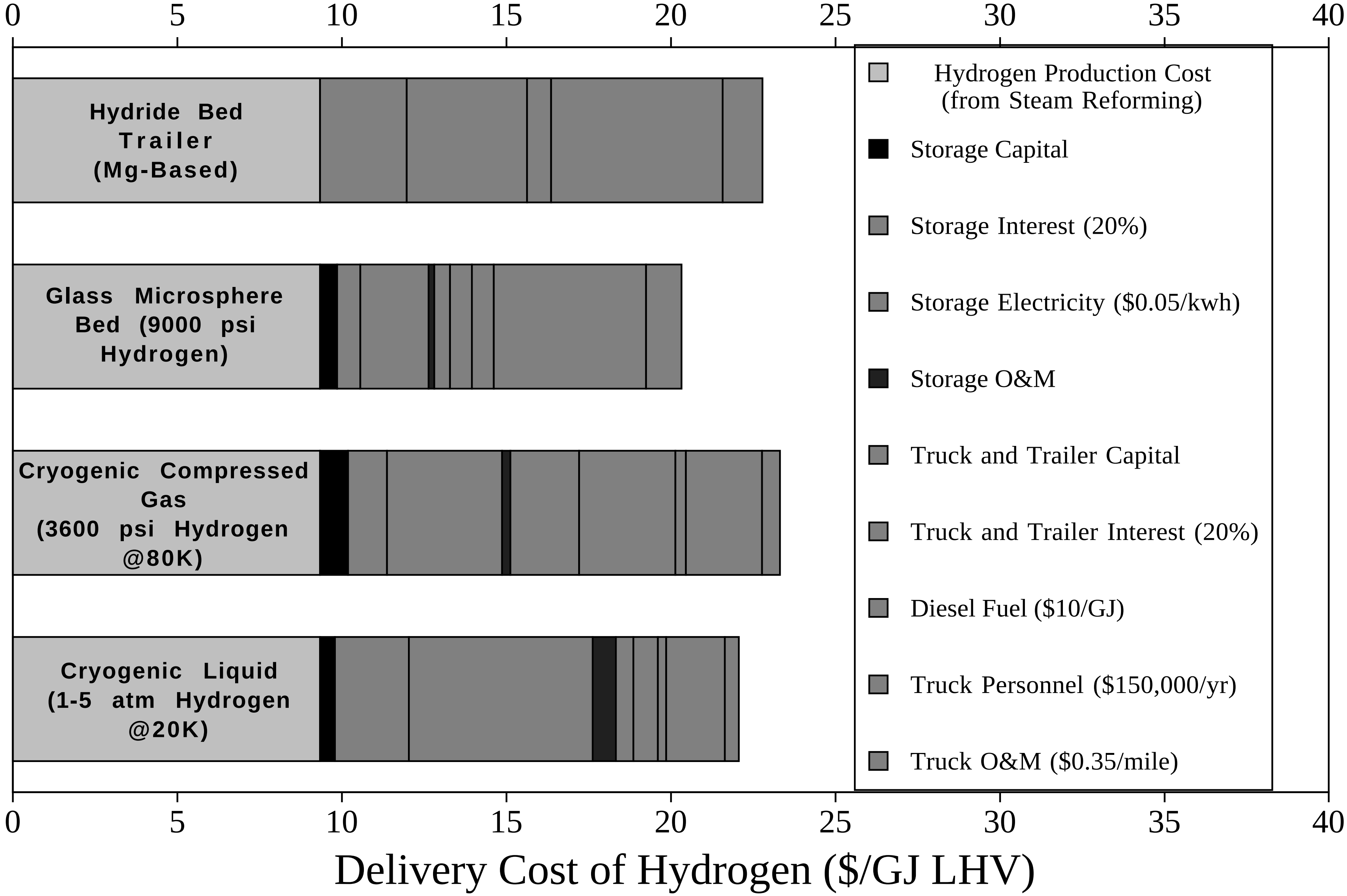

Figure 5. The cost components of hydrogen delivered 250 miles by truck using four different mobile hydrogen storage technologies. Hydrogen is assumed to be produced for \$9.30/GJ at a large steam methane reforming plant. Electricity for hydrogen storage is assumed to cost \$0.05/kWh. Capital equipment is discounted at 20% over 10 years. Trucks travel 100,000 miles/yr, and associated personnel costs are assumed to be \$150,000/yr. Liquid hydrogen (LH_2) trucks have low capital investment and low operating costs (lined patterns) but high fixed-storage costs (fill patterns). The alternative technologies each store less hydrogen than LH_2 trucks, so variable operating costs are higher. The alternative technologies have lower fixed-storage costs because of lower energy requirements. Each technology could deliver centrally produced hydrogen over a distance of 250 miles for roughly \$20–25/GJ.

Figure 6. The Effect of Delivery Distance and Storage Technology on the Cost of Hydrogen Delivery by Truck

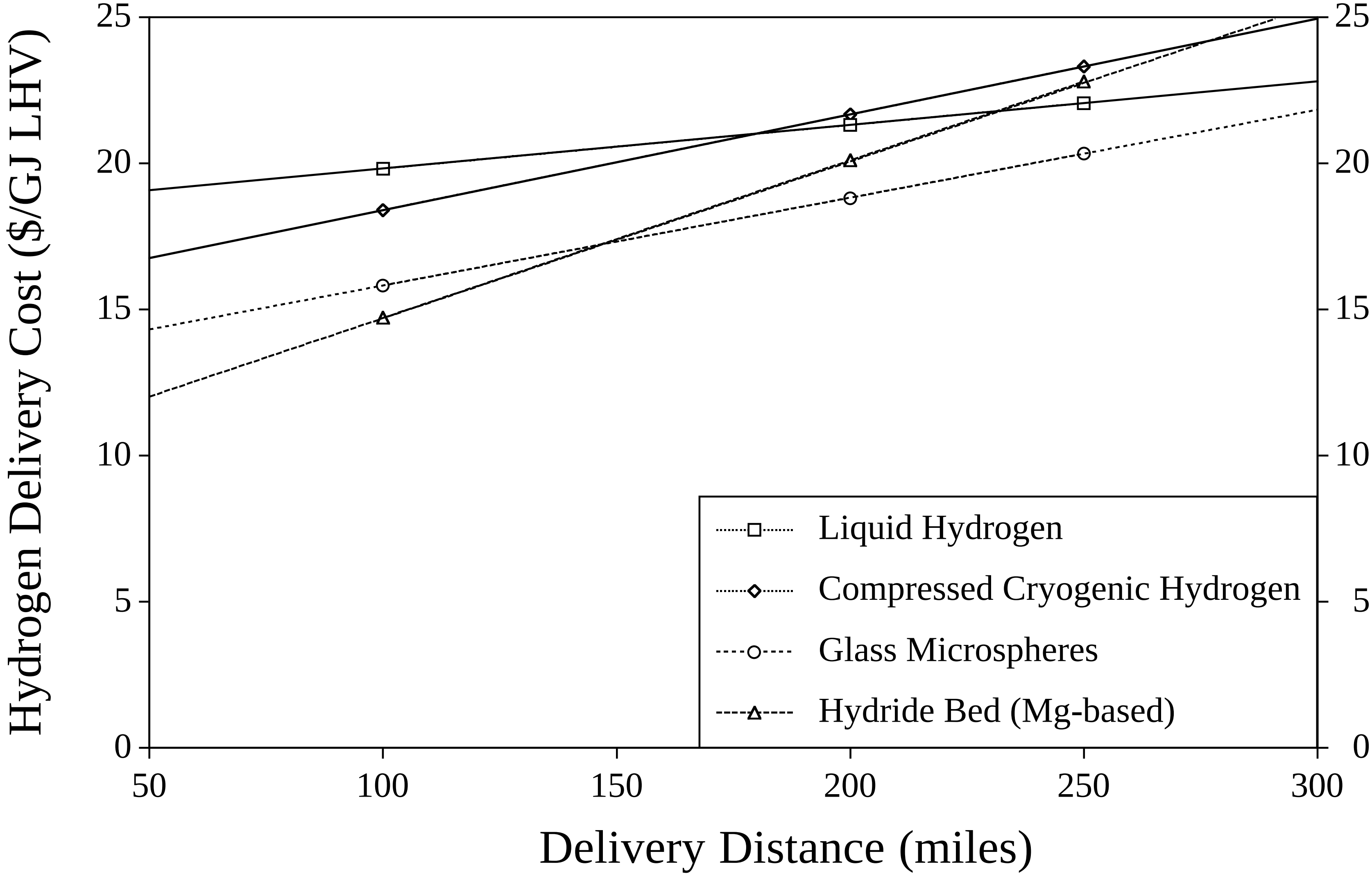

Figure 6. The estimated costs of truck-delivered hydrogen using four different storage technologies—magnesium-based hydride, microspheres, LH_2, and cryogenic (80 K) hydrogen gas (3600 psi)—are shown as a function of delivery distance. Economic assumptions are the same as in Fig. 5. Alternatives to LH_2 delivery are much more cost-sensitive to delivery distance but could offer some benefit for short deliveries (<150 mile). Microspheres appear to be the most promising of the alternatives.

Figure 7. Cost Breakdown of 7 Hydrogen Pathways for Stations, Fleets, and Homes (broken down by pathway step)

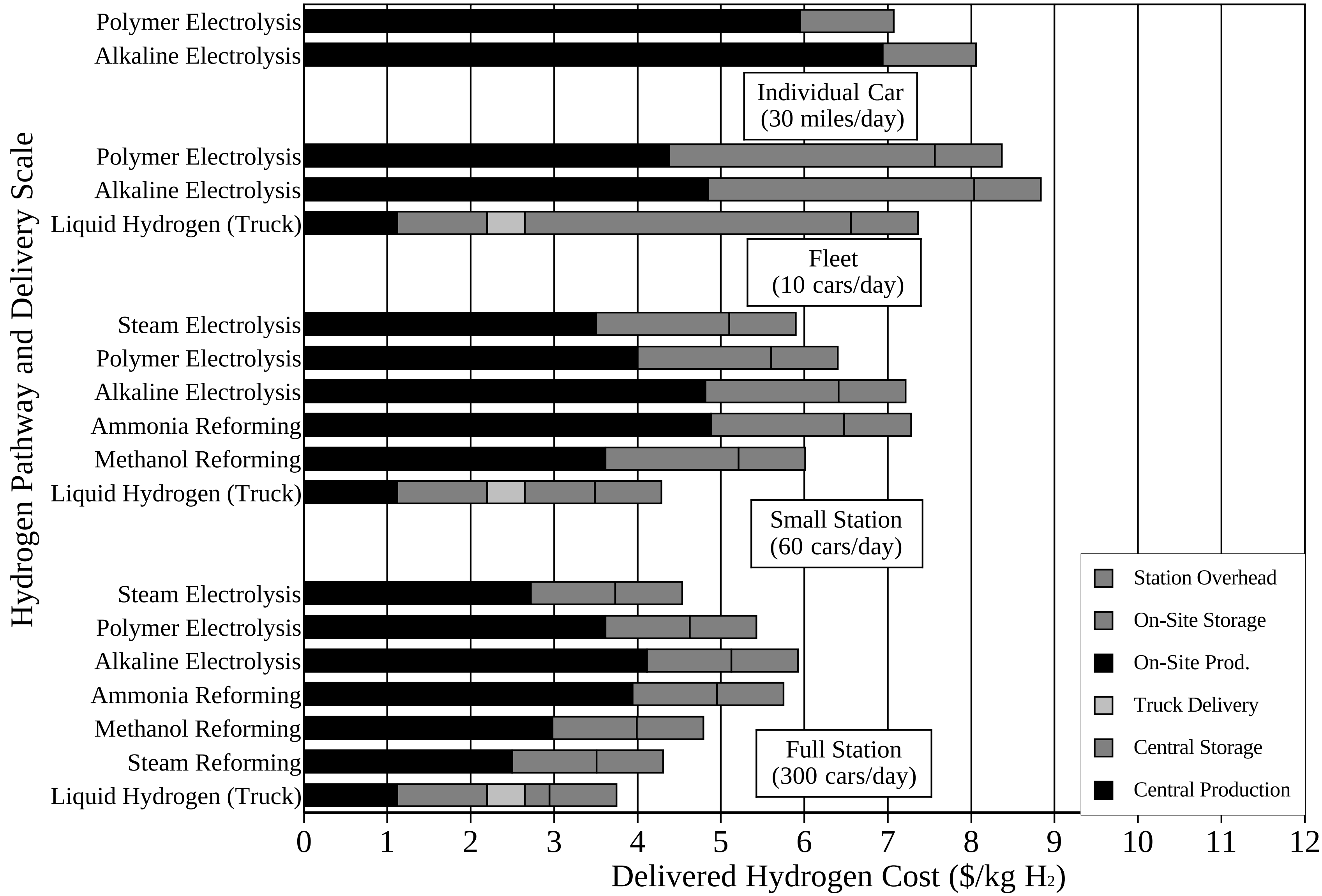

Figure 7. The costs of production, storage, and delivery of hydrogen at four scales, broken down by process steps, are shown for seven hydrogen pathways: (1) LH_2 delivery by truck, (2) on-site steam-reforming from \$4.00/GJ natural gas, (3) on-site methanol reforming from \$0.66/gallon methanol, (4) on-site ammonia cracking from \$250/ton ammonia, (5) conventional alkaline electrolysis, (6) polymer membrane electrolysis, and (7) steam electrolysis. Off-peak electricity costs are \$0.05/kWh. Discount rates are 20% for stations, 10% for individual vehicle systems. Note that individual-vehicle refueling using home electrolysis has compressed gas storage for 1 kg of hydrogen.

Figure 8. Cost Breakdown of 7 Hydrogen Pathways for Stations, Fleets, and Homes (broken down by cost element)

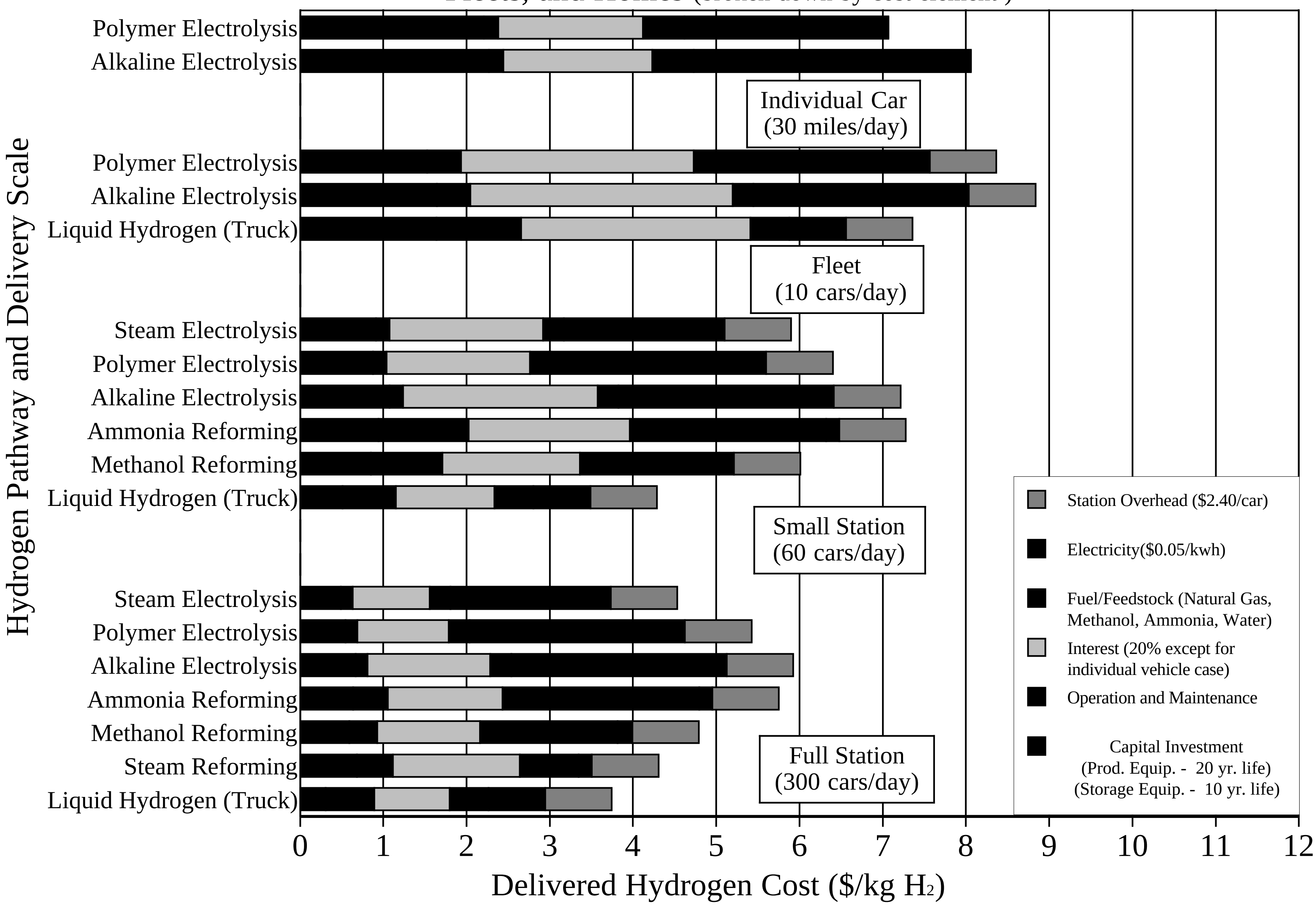

Figure 8. The costs of production, storage, and delivery of hydrogen at four scales—broken down into capital recovery, interest, energy, overhead, and operations and maintenance costs—are shown for seven hydrogen pathways: (1) LH_2 delivery by truck, (2) on-site steam reforming from $4.00/GJ natural gas, (3) on-site methanol reforming from $0.66/gallon methanol, (4) on-site ammonia cracking from $250/ton ammonia, (5) conventional alkaline electrolysis, (6) polymer membrane electrolysis, and (7) steam electrolysis. Off-peak electricity costs are $0.05/kWh. Discount rates are 20% for stations, 10% for individual vehicle systems. Equipment life is 20 years for production and 10 years for storage.

Figure 9. Cost Breakdown of 7 Hydrogen Pathways for Stations, Fleets, and Homes (broken down by pathway step and cost type)

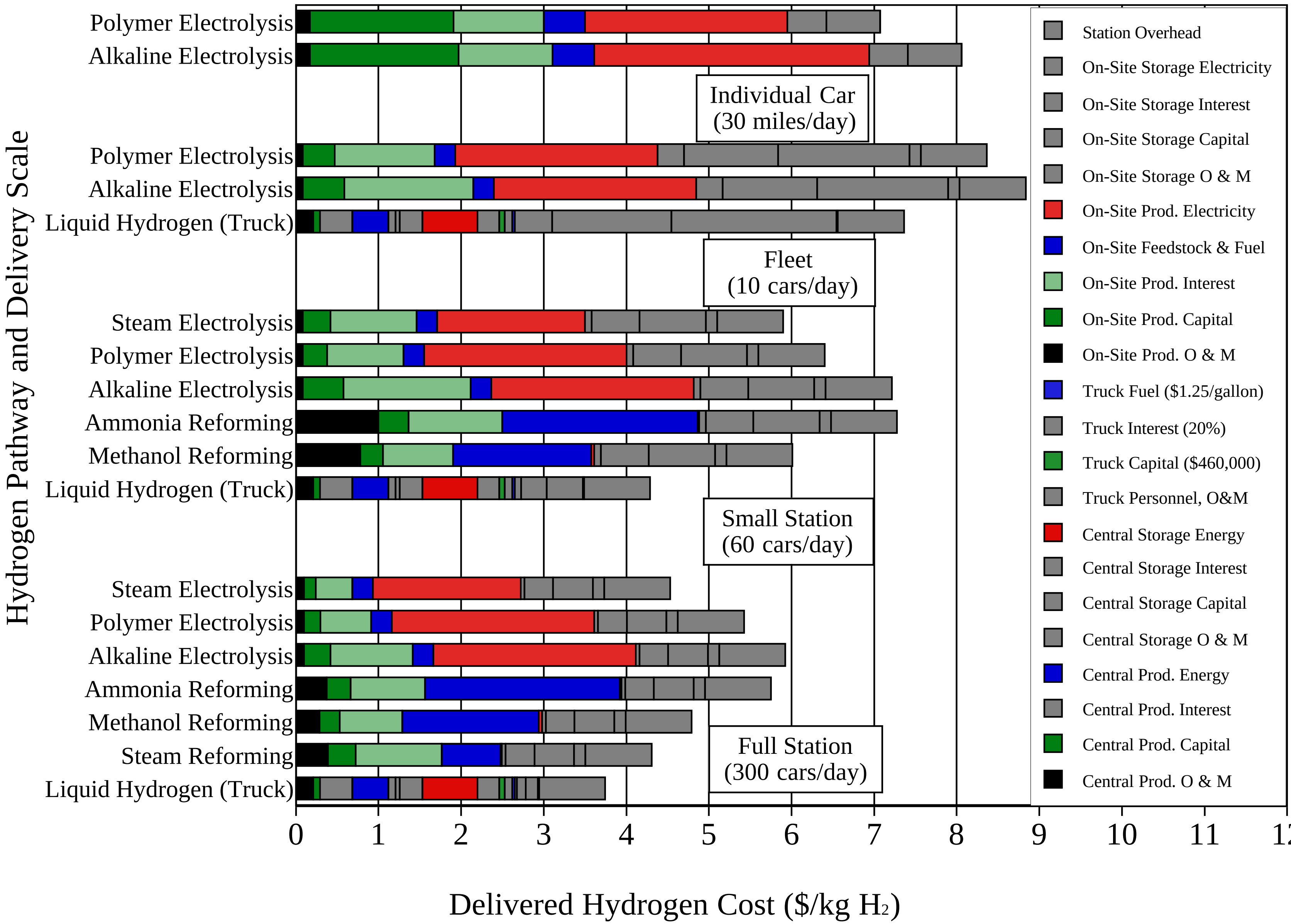

Figure 9. Detailed cost breakdown for production, storage, and delivery of hydrogen at four scales—broken down into capital recovery, interest, energy, overhead, and operations and maintenance costs of each process step—are shown for seven hydrogen pathways: (1) LH_2 delivery by truck, (2) on-site steam reforming from $4.00/GJ natural gas, (3) on-site methanol reforming from $0.66/gallon methanol, (4) on-site ammonia cracking from $250/ton ammonia, (5) conventional alkaline electrolysis, (6) polymer membrane electrolysis, and (7) steam electrolysis. Off-peak electricity costs are $0.05/kWh. Discount rates are 20% for stations, 10% for individual vehicle systems. Equipment life is 20 years for production and 10 years for storage. Note that $/kg of hydrogen can be changed to $/GJ by an 8.33 multiplier.

Figure 10. Primary & Process Energy Requirements for Hydrogen Production, Delivery, and Storage

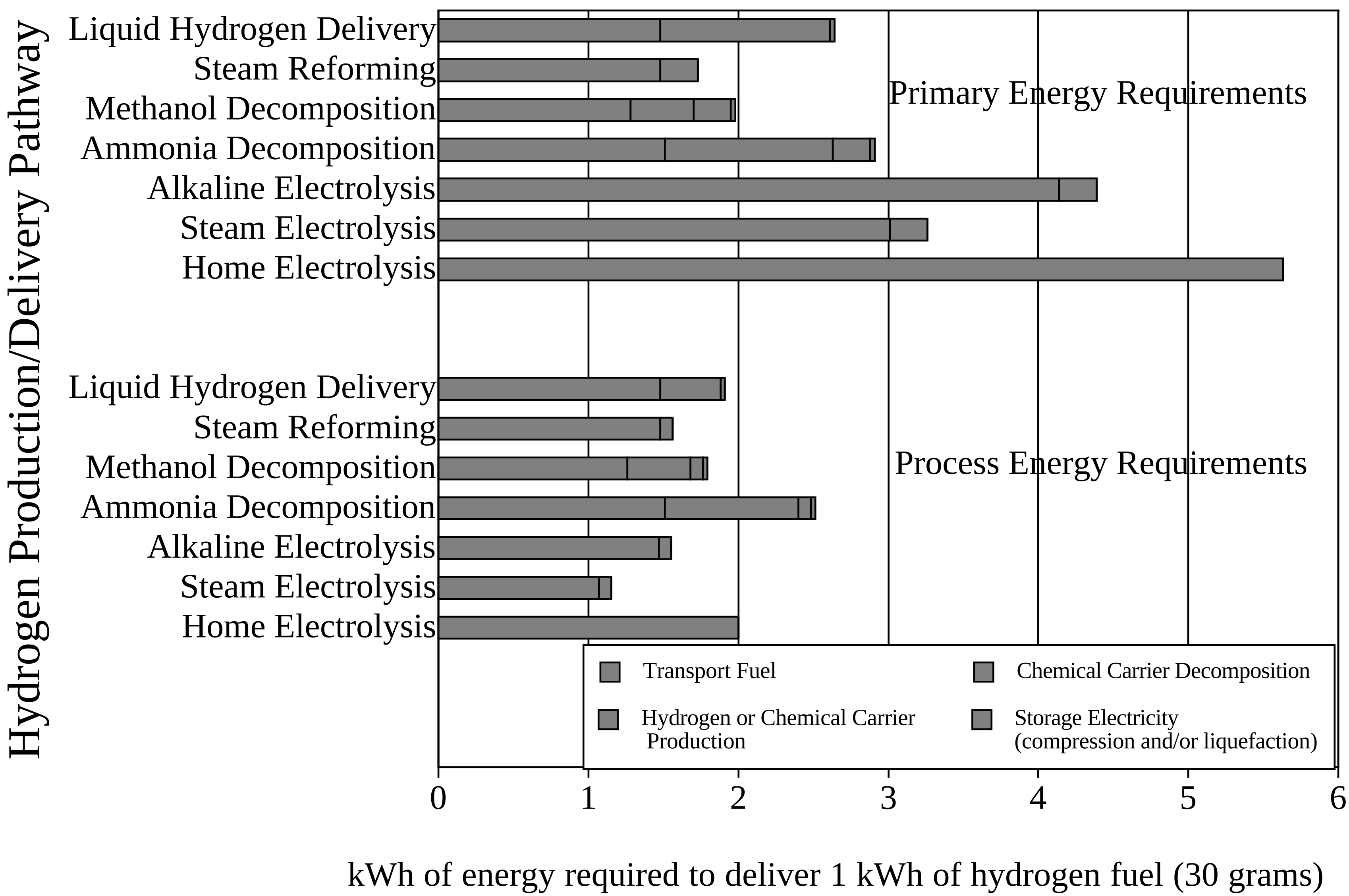

Figure 10. The primary energy and process energy requirements for the stages of seven hydrogen pathways are shown in kilowatt-hours of energy input per kWh of hydrogen delivered. *Process* energy requirements to deliver 1 kWh of hydrogen range from 1.2 kWh (steam electrolysis) to 2.5 kWh (ammonia decomposition at a hydrogen filling station.) If the electricity for compression and/or liquefaction steps is generated from fossil energy through a steam cycle, then the *primary* energy requirements increase sharply for all hydrogen pathways except for on-site steam reforming and hydrogen carrier (ammonia or methanol) decomposition. Primary energy requirements can then range from nearly 2 to 5.5 kWh per kWh of hydrogen delivered. Process step efficiencies are principally taken or adapted from Ref. 14, 21, and 22.

Figure 11. Estimated Greenhouse Gas Emissions in 2005 for Passenger Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using natural gas for primary energy)

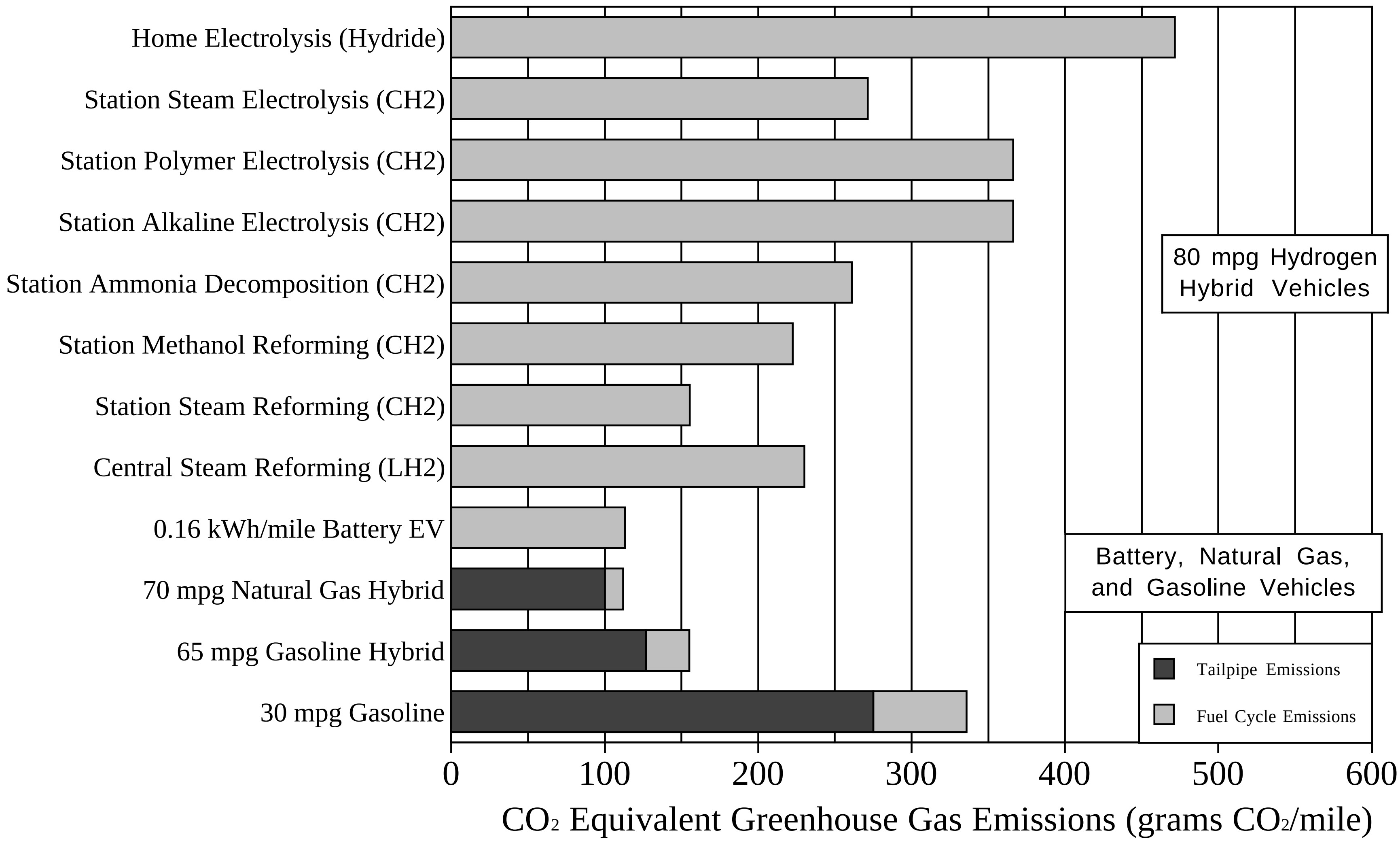

Figure 11. Greenhouse CO_2-equivalent emissions are shown for five vehicles with equivalent power requirements: a conventional gasoline 30-mpg car, a 65-mpg gasoline HEV, a 70-mpg natural-gas HEV, a BPEV achieving 0.16 kWh / mile, and an 80-mpg hydrogen HEV. Emissions for the hydrogen car are based on the seven hydrogen pathways and energy requirements shown in Fig. 10 and projected to the year 2000 from Ref. 35. It can be seen that if natural gas is the primary energy source under consideration, 80-mpg hydrogen vehicles can reduce greenhouse gas emissions below today's gasoline cars, but even the most energy-efficient hydrogen pathway (station steam-reforming) produces the same emissions as a 65-mpg gasoline hybrid car. Natural-gas HEVs and BPEVs offer *significantly lower* greenhouse-gas emissions than gasoline or hydrogen vehicles.

Figure 12. Estimated Air Pollutant Emissions in 2005 for Passenger Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using natural gas for primary energy)

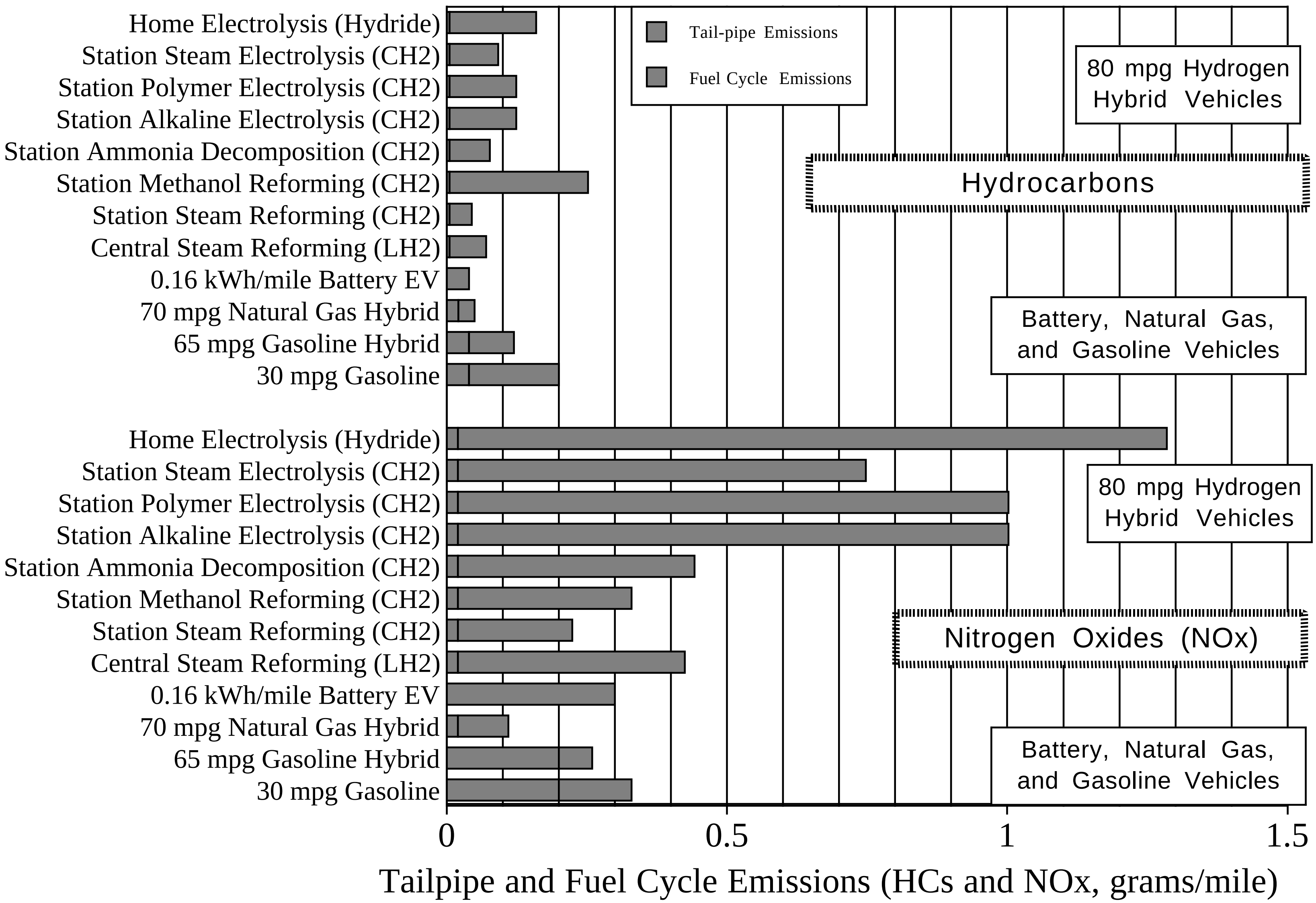

Figure 12. Estimated tailpipe and fuel-cycle emissions of nitrogen oxides (NOx) and hydrocarbons are shown for the five vehicles and seven hydrogen pathways in Fig. 11. Projected 2005 emission factors were taken from Ref. 35. It can be seen that on a full-fuel-cycle basis, hydrogen vehicles using natural gas as a primary energy source provide no NOx emissions benefit over ULEV (or lower) non-hydrogen vehicles. There are some hydrocarbon emission benefits for hydrogen vehicles over gasoline vehicles, but natural-gas HEVs and BPEVs produce lower emissions of both NOx and hydrocarbons than gasoline vehicles. It also appears that NOx full-fuel-cycle emissions is the primary air pollutant issue facing hydrogen vehicles.

Figure 13. Tailpipe Emissions of Hybrid Electric Vehicles using Hydrogen, Natural Gas, and Gasoline

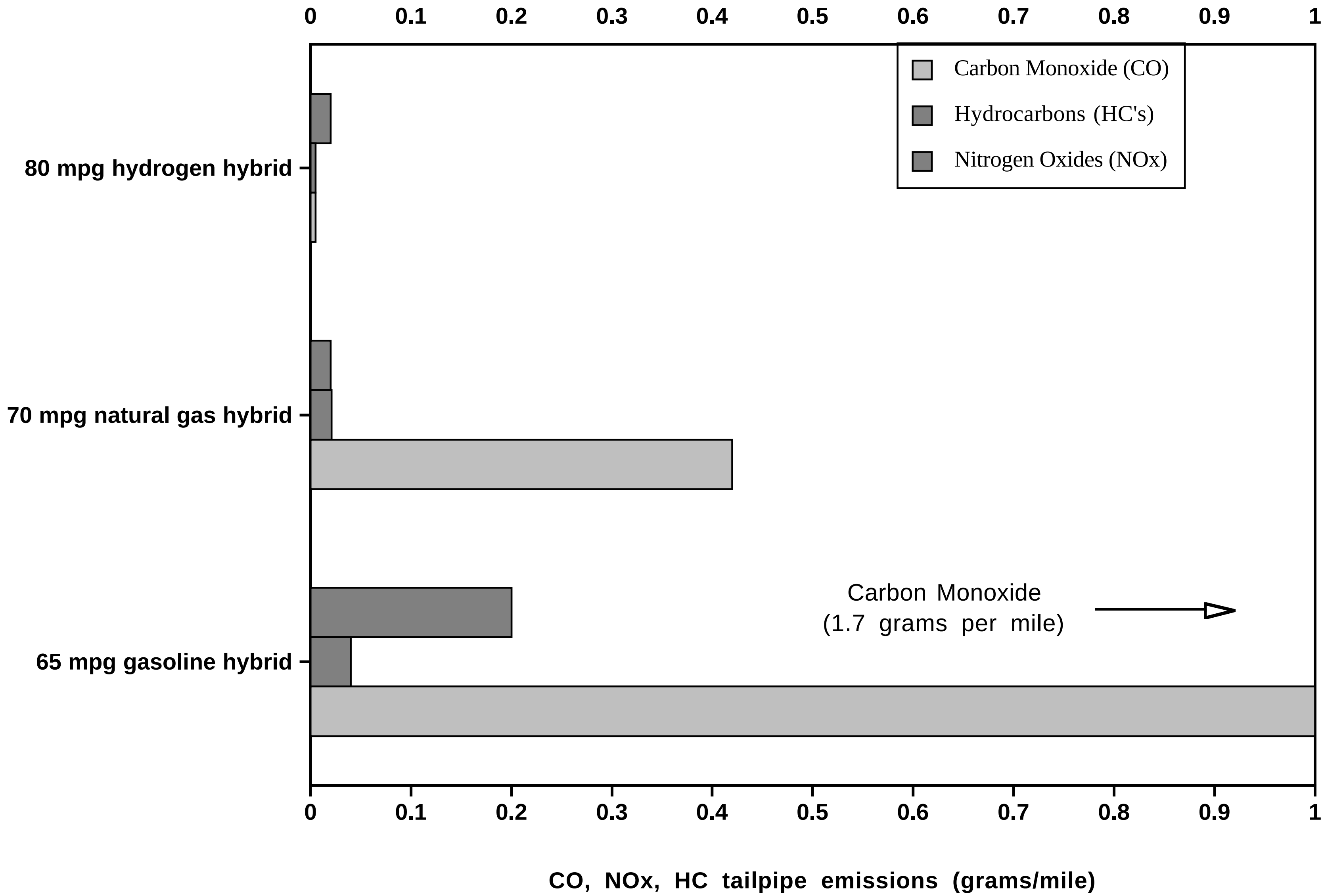

Figure 13. Tailpipe emissions of CO, hydrocarbons, and NOx are shown for hydrogen, natural gas, and gasoline HEVs. Ultra-low emission vehicle (ULEV) standards are used to represent emissions from a gasoline hybrid. Emissions from a natural-gas HEV are based upon recent certification tests of Chrysler's NGV minivan (Ref. 35). Hydrogen vehicle tailpipe emissions are from Ref. 5 and 34. It can be seen that both hydrogen and natural-gas vehicles offer tailpipe emission levels many times lower than ULEV standards, but the only in the case of CO do hydrogen vehicles provide significant emissions benefits over natural gas.

Figure 14(a). Electric Generating Supply Mix and Average CO_2 and NO_x Emissions for "Reference" Scenario (2005-2050)

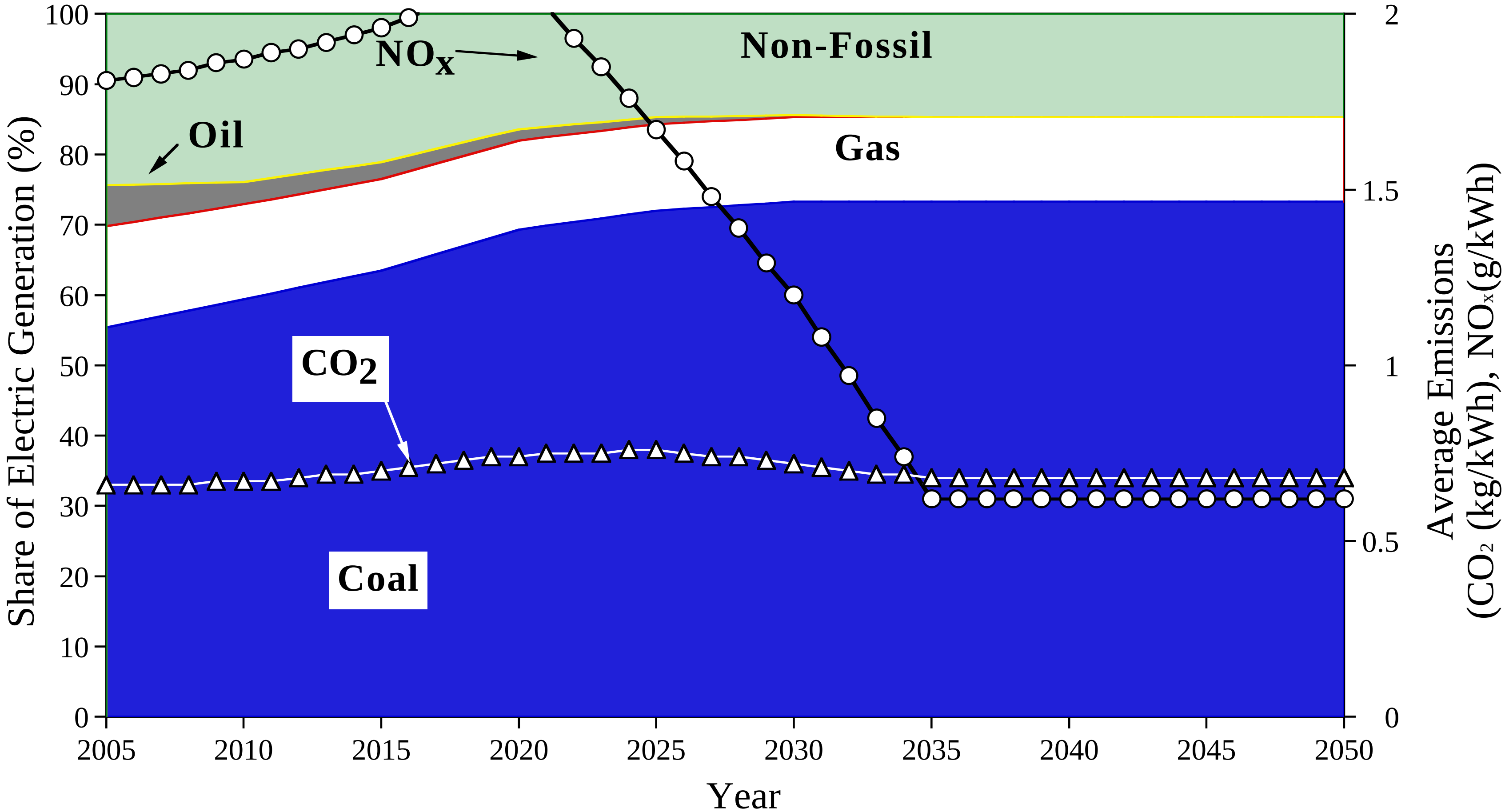

Figure 14(b). Electric Generating Supply Mix and Average CO_2 and NO_x Emissions for "Market" Scenario (2005-2050)

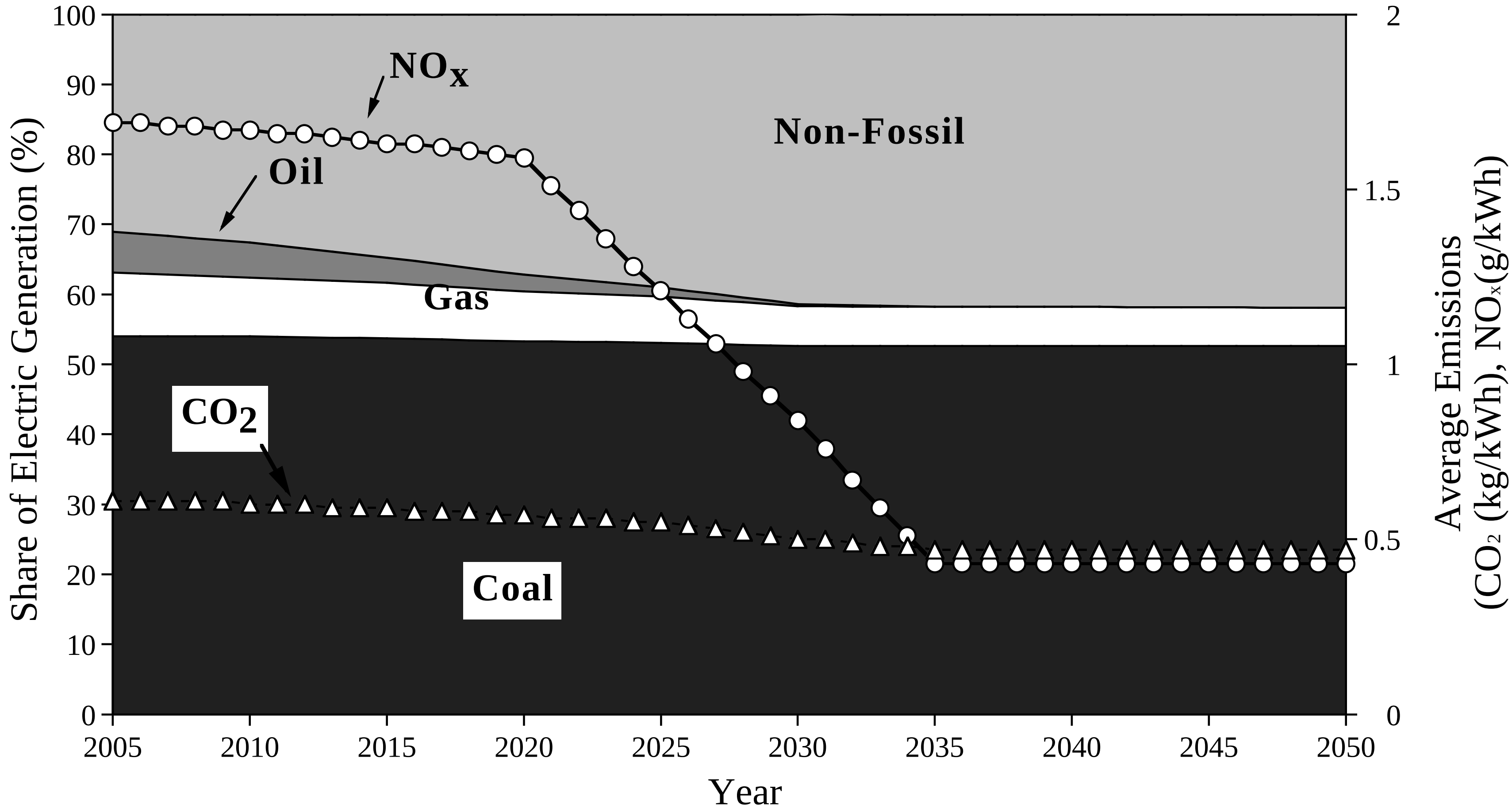

Figure 14(c). Electric Generating Supply Mix and Average CO_2 and NO_x Emissions for "Climate" Scenario (2005-2050)

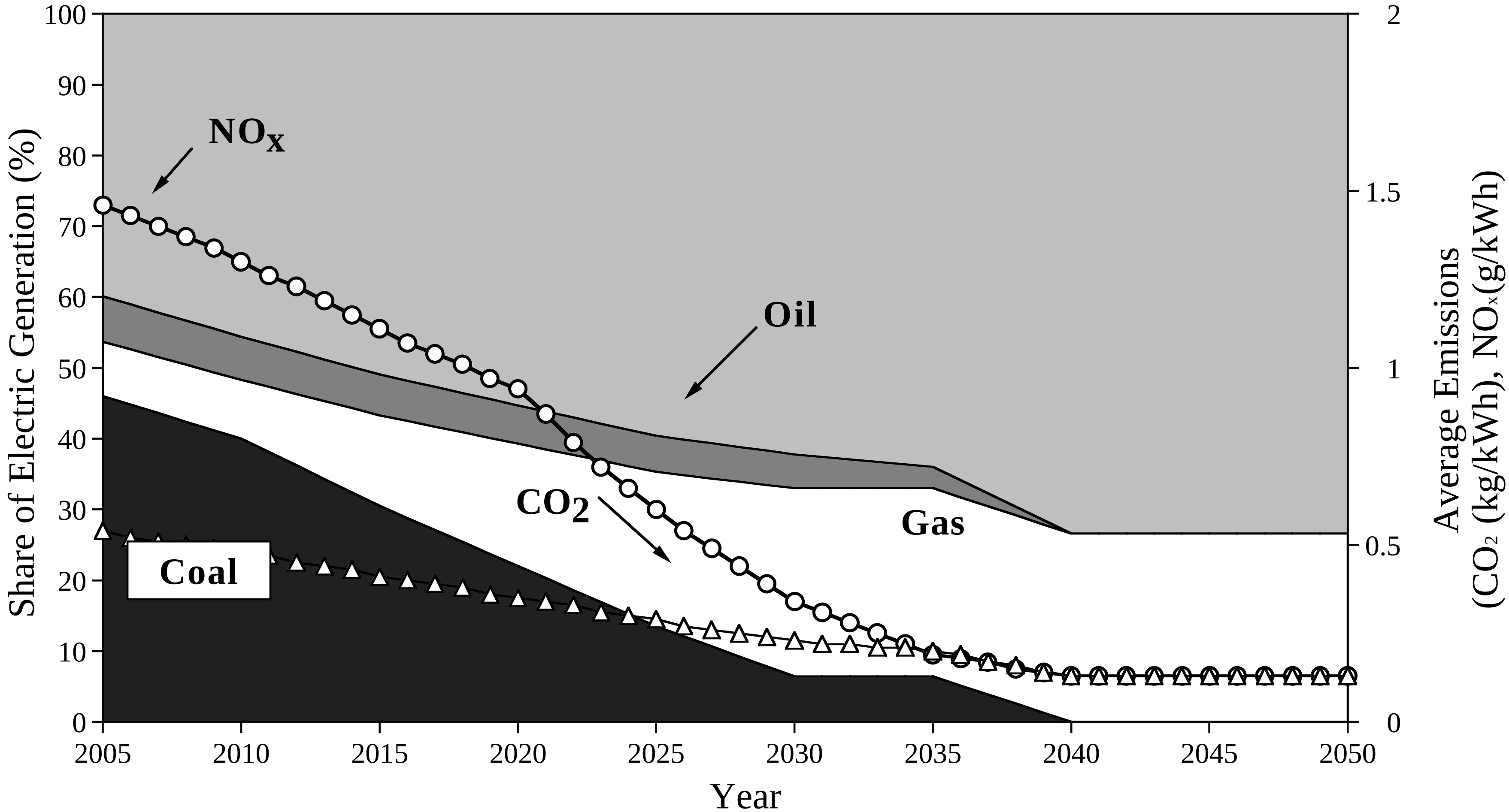

Figure 14(a-c). Electricity-generation primary energy supply mix and associated average full-fuel-cycle emissions of greenhouse gases (kg of CO_2 equivalent) and NOx are shown for three electricity-mix scenarios spanning the period 2005 to 2050. The scenarios were adapted from Ref. 36. Figure 14(a) describes a “reference” scenario in which the share of coal-based generation grows from 55% to 70% from 2005 to 2030 at the expense of oil-based and non-fossil generation, with natural-gas-based generation retaining a steady share of 15%. Figure 14(b) describes a “market” scenario in which market barriers to non-fossil generation are diminished, increasing the share of non-fossil generation from 30% to 40%, reducing gas-based generation, and eliminating oil-based generation, while coal remains steady. Figure 14(c) describes a “climate” scenario in which greenhouse-gas emission reductions are a long-term driver. Coal-based generation is eliminated by 2040, initially replaced by retaining oil generation, but ultimately by increasing natural-gas generation from 10% to 30% and non-fossil generation from 40% to 70% of electricity production.

Emissions for all three scenarios were based chiefly on Ref. 35 and 36 and on the Department of Energy’s “Hydrogen Program Plan, FY1993–FY1997” (DOE/CH10093-147 DE92010556, 1992), using conventional steam generation for each fuel type but phasing in cleaner and more efficient combined-cycle plants between 2020 and 2035. NOx and CO_2 emissions for non-fossil generation were assumed to be essentially zero. Average NOx emission rates drop from roughly 1/3 to 1/10 of emissions in 2005 by the 2035–2040 timeframe, depending upon scenario. Average CO_2 emission rates increase slightly between 2005 and 2050 or drop by up to 75%, depending upon scenario.

Figure 15(a). Estimated Greenhouse Gas Emissions in 2005 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Reference Case" Electric Generation Mix)

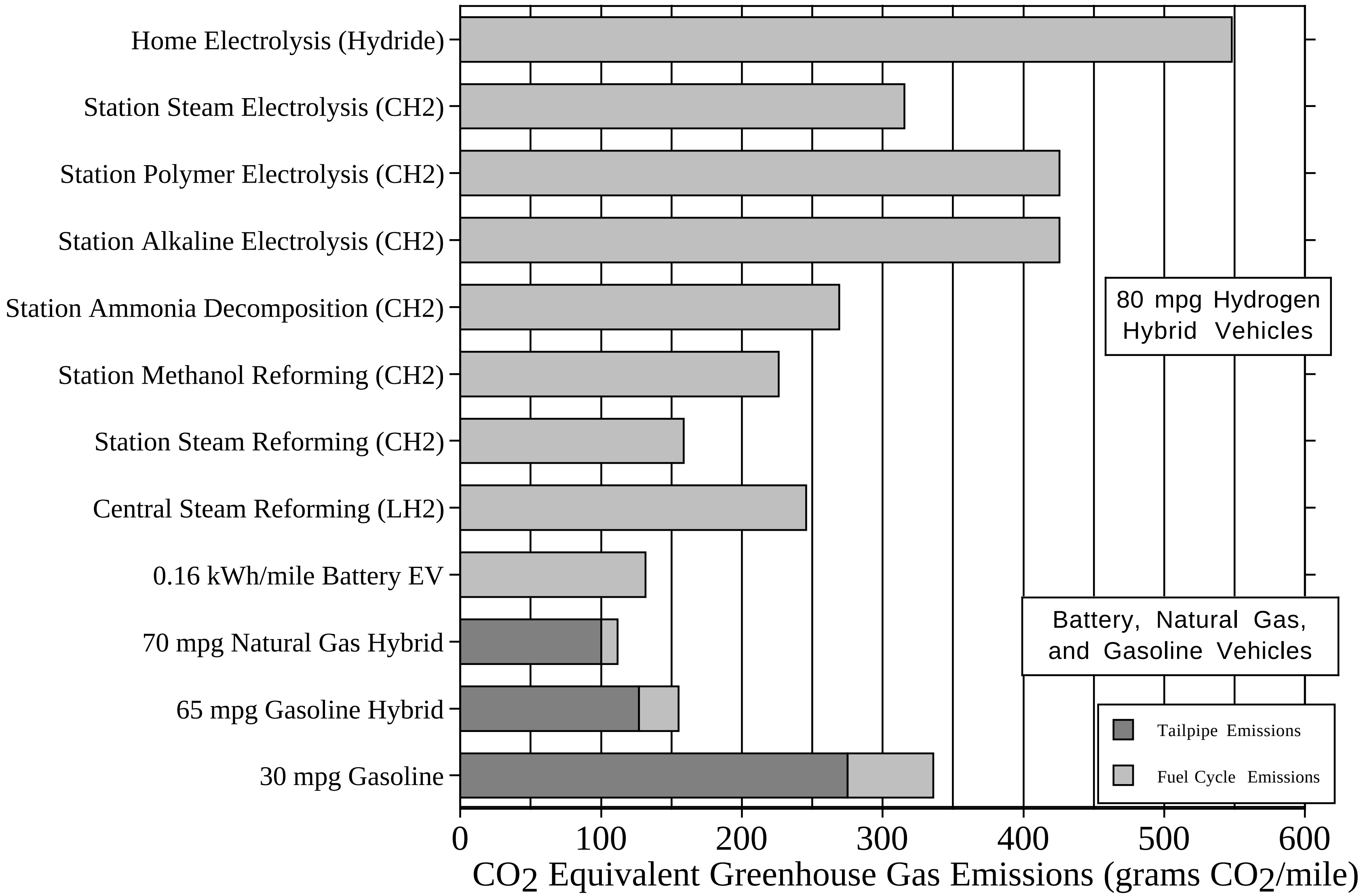

Figure 15(b). Estimated Greenhouse Gas Emissions in 2035 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Reference Case" Electric Generation Mix)

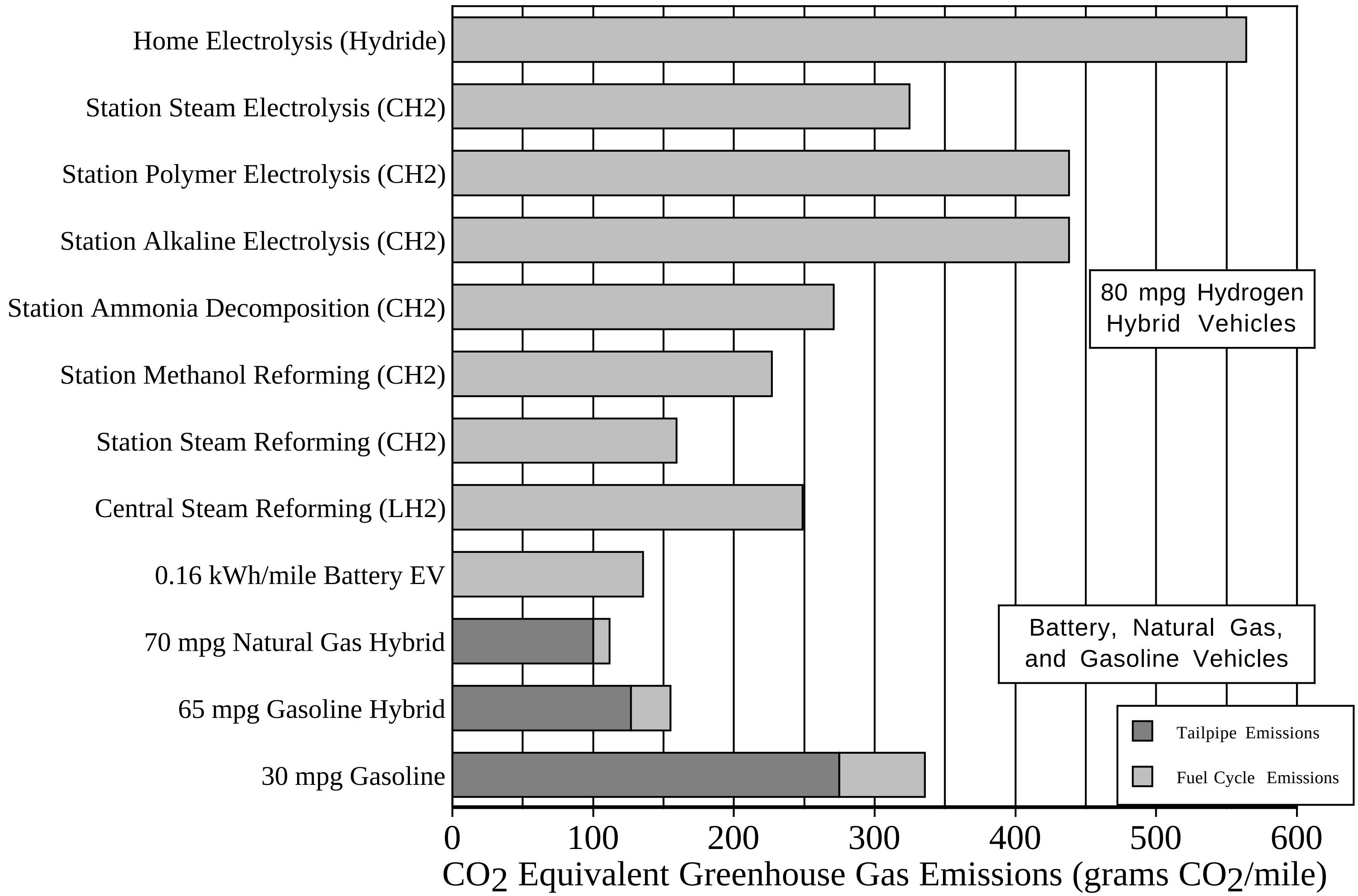

Figure 15(c). Estimated Greenhouse Gas Emissions in 2035 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Market Case" Electric Generation Mix)

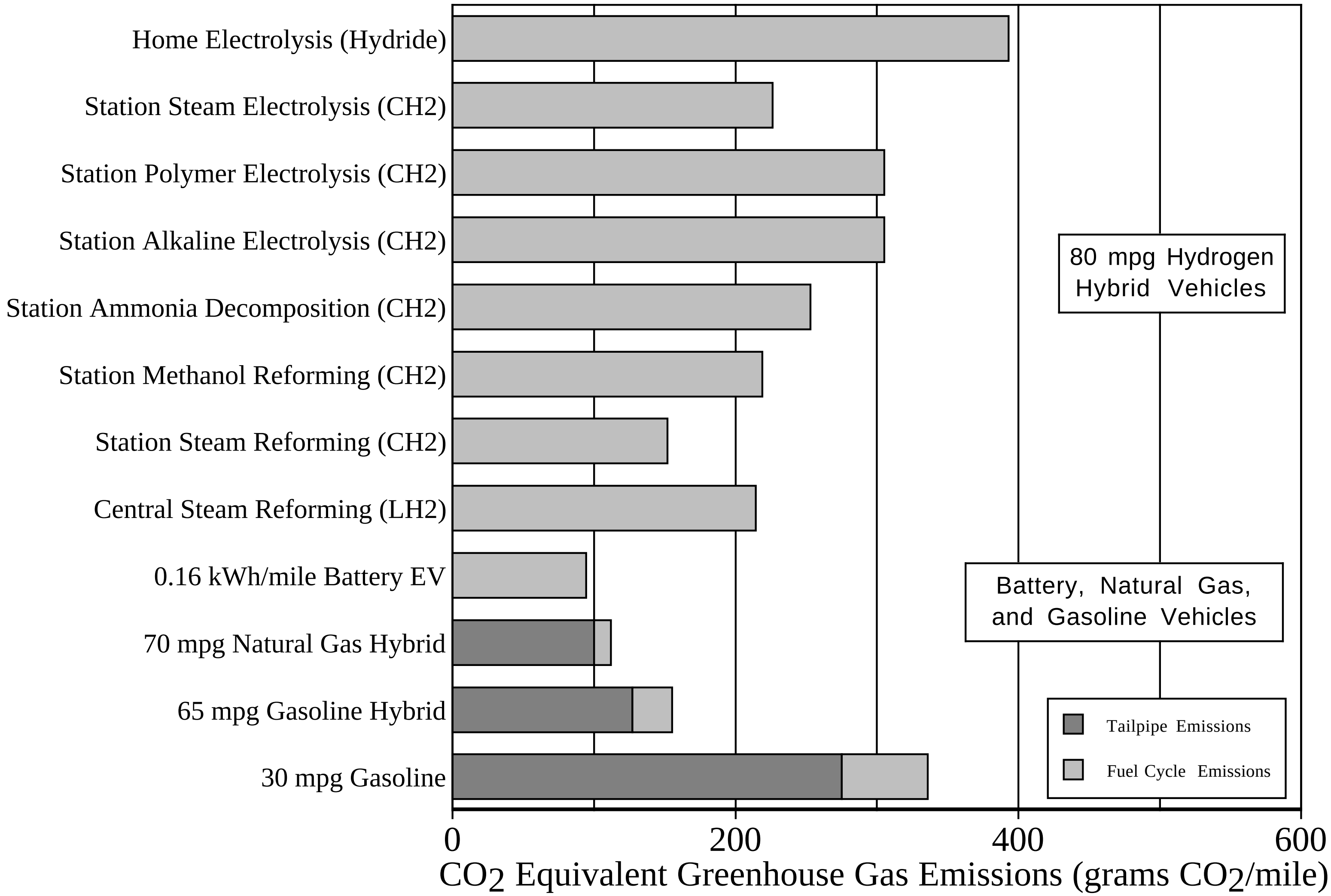

Figure 15(d). Estimated Greenhouse Gas Emissions in 2035 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Climate Case" Electric Generation Mix)

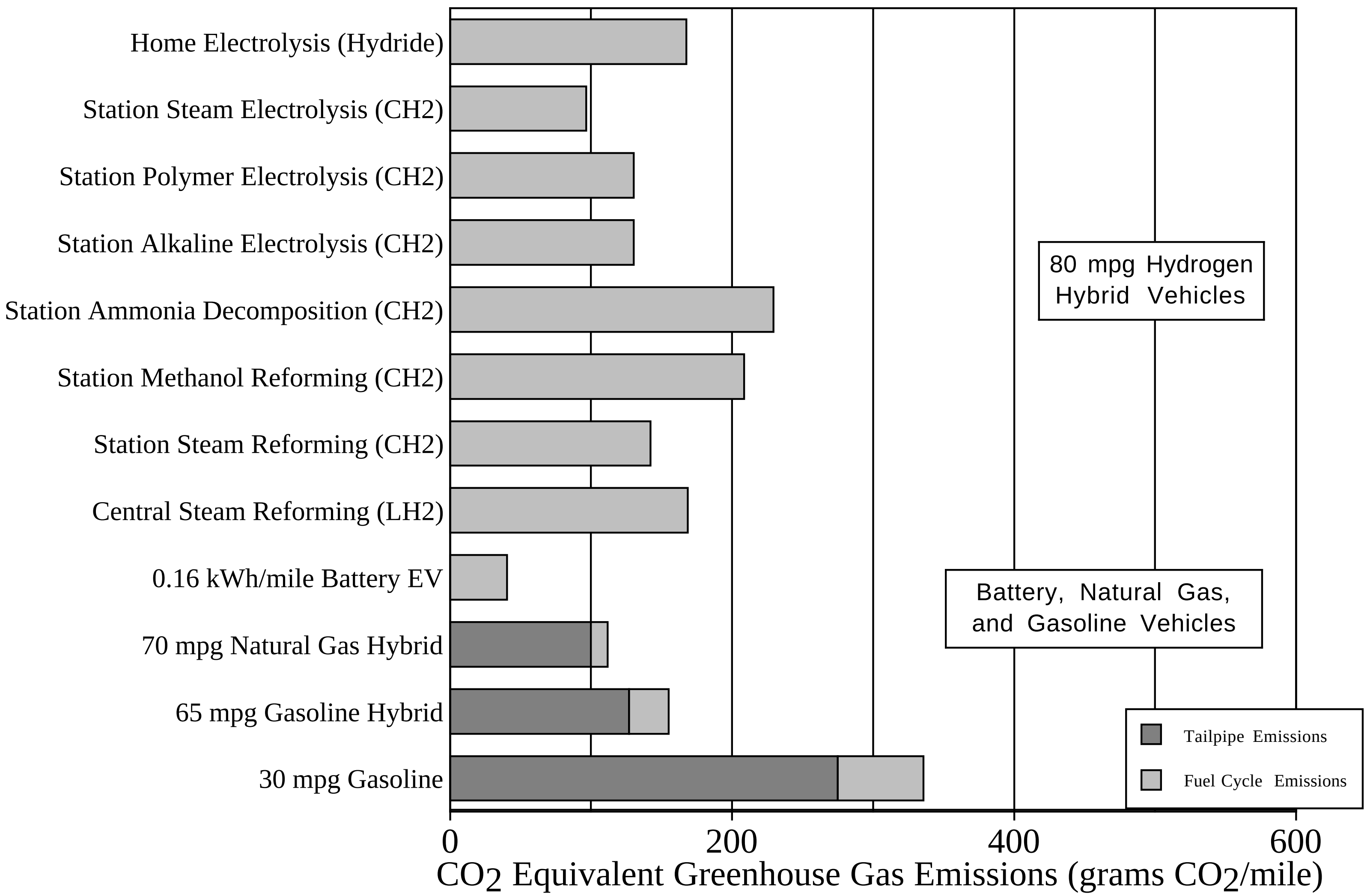

Figure 15(a-d). Four snapshots of full-fuel-cycle greenhouse-gas emissions (in CO_2-equivalent grams per mile) are shown for the same five vehicles and seven hydrogen pathways used in Fig. 11 and 13, but using the three electricity mix scenarios of Fig. 14 in 2005 and 2035. Emissions are reduced significantly with changes in electricity-generation mix. Figure 15(a) shows emissions under the "reference" scenario in 2005. Figure 15(b) shows that emissions in 2035 increase slightly under the "reference" scenario. Figure 15(c) shows that emissions decrease roughly 25% for electricity-intensive pathways in 2035, under the "market" scenario. Figure 15(d) shows that emissions decrease sharply in 2035 under the "climate" scenario. Figure 15(b-d) also shows that under the "reference" case hydrogen cars are inferior to fossil-fuel hybrid vehicles and battery cars in 2035, while electrolytic hydrogen cars only achieve emission levels comparable to 30-mpg gasoline vehicles. The emissions of hydrogen cars can equal or better 30-mpg gasoline cars under the "market" scenario, but natural-gas hybrids and battery vehicles still offer significantly lower emissions. Under the "climate" scenario, a number of interesting changes occur by 2035. First, electrolytic hydrogen pathways offer lower or comparable emissions than thermochemical hydrogen pathways using natural gas or hydrogen carriers manufactured from natural gas, and even lower emissions than gasoline vehicles, comparable to greenhouse-gas emissions from a natural-gas HEV. If hydrogen is produced from high-efficiency steam electrolysis, or similar methods, then hydrogen cars achieve lower emissions than fossil-fuel HEVs, roughly one third of 30-mpg gasoline vehicle emissions.

Figure 16(a). Estimated Air Pollutant Emissions in 2005 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Reference Case" Electric Generation Mix)

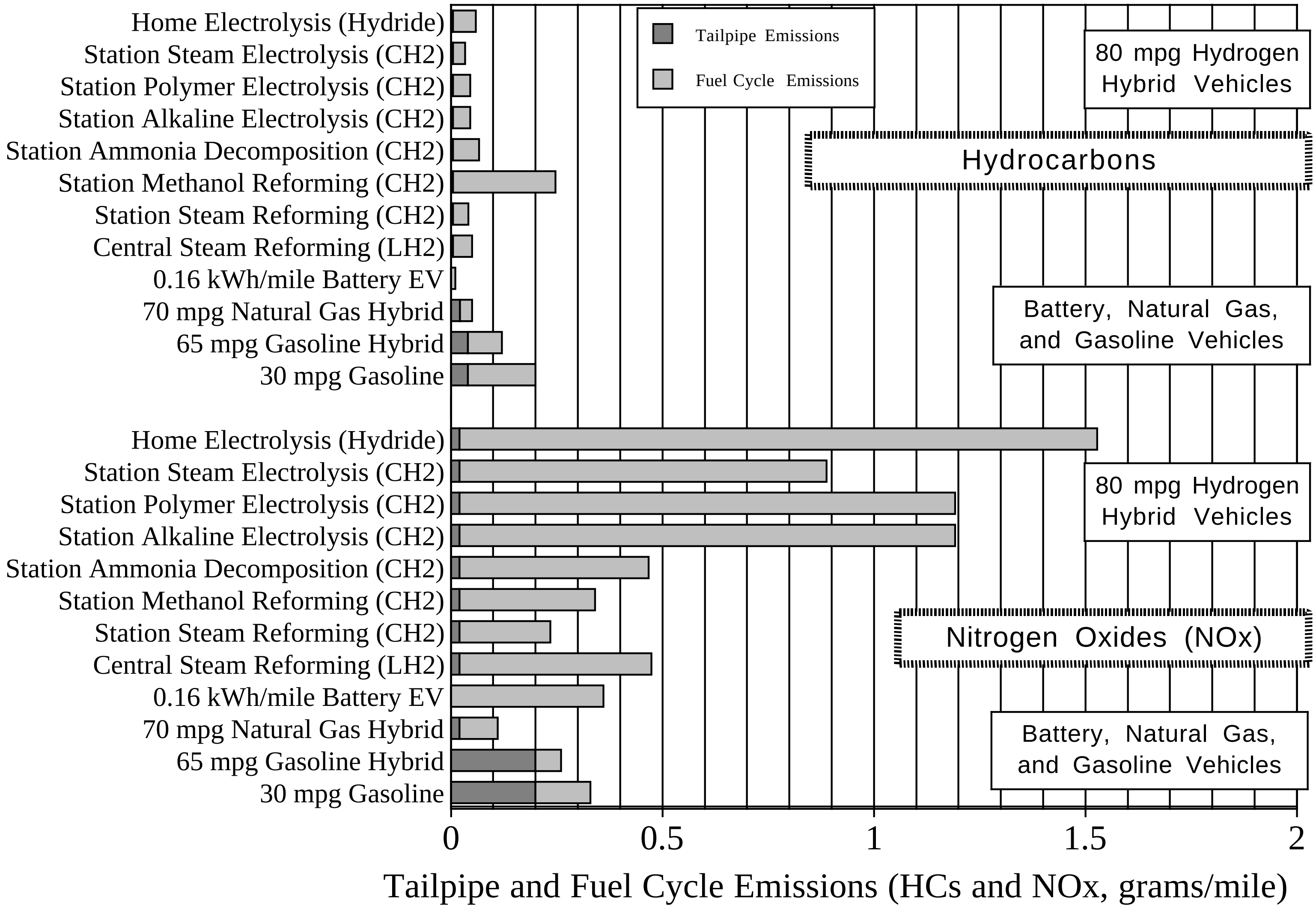

Figure 16(b). Estimated Air Pollutant Emissions in 2035 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Reference Case" Electric Generation Mix)

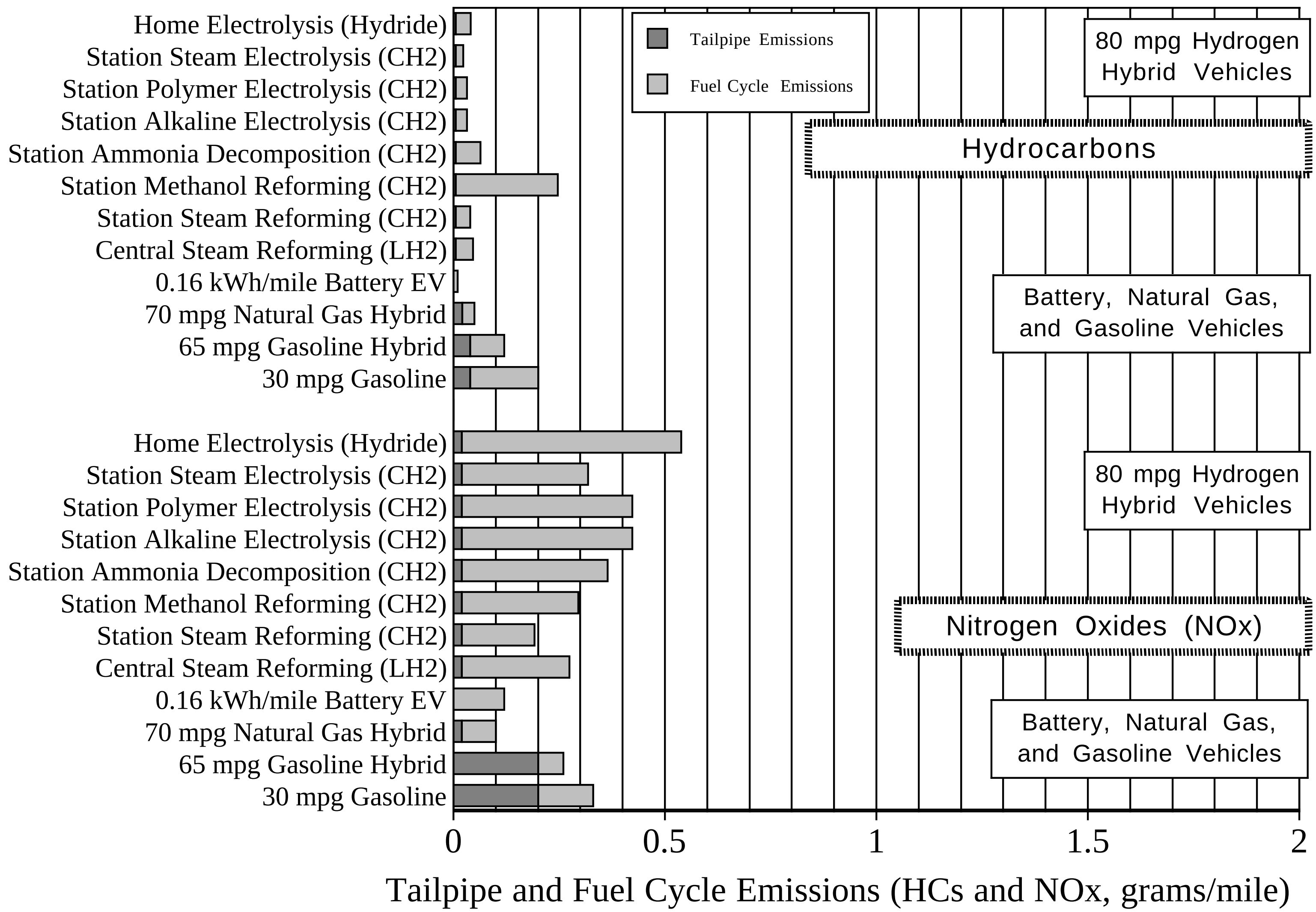

Figure 16(c). Estimated Air Pollutant Emissions in 2035 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Market Case" Electric Generation Mix)

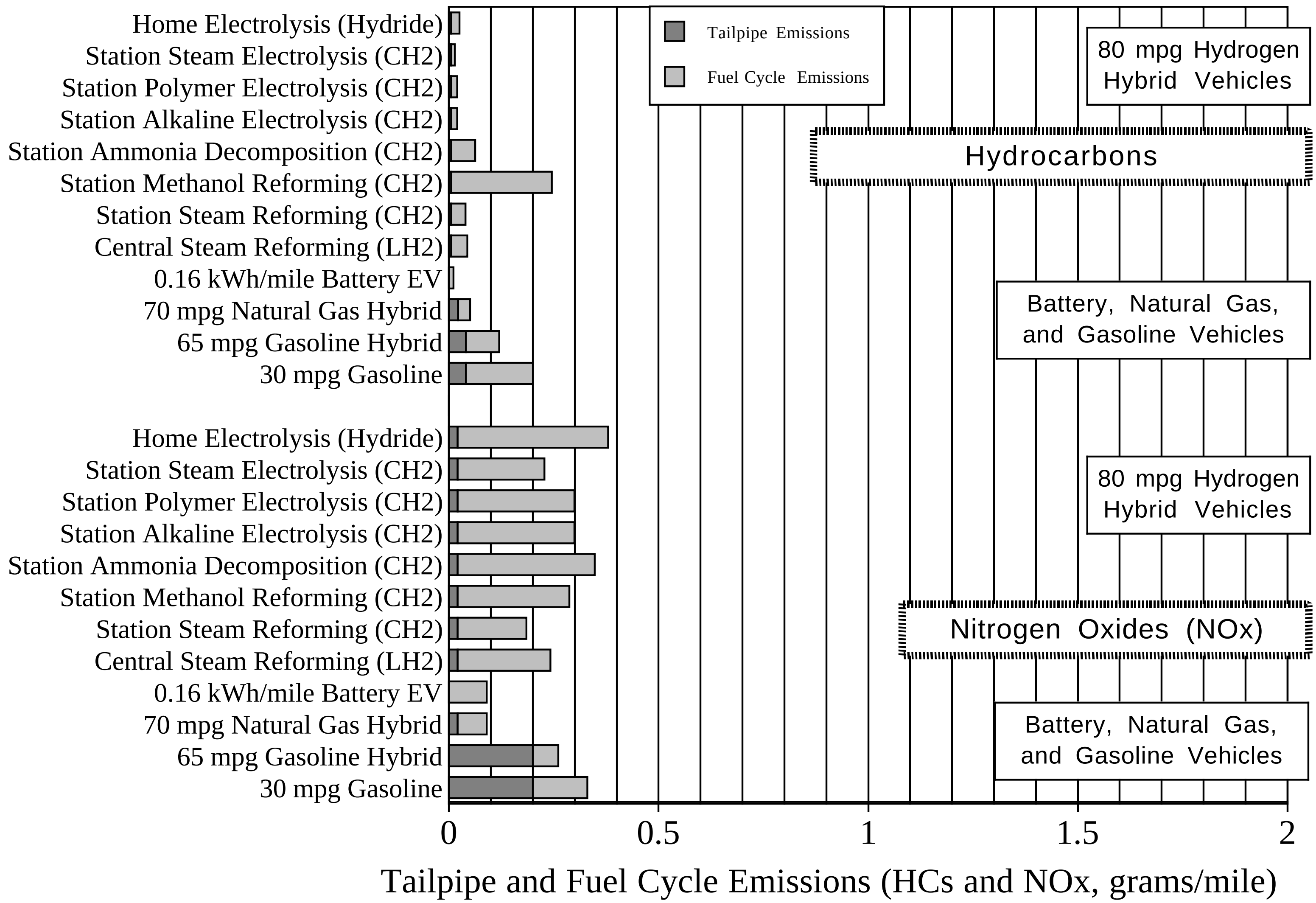

Figure 16(d). Estimated Air Pollutant Emissions in 2035 for Cars Fueled by Hydrogen, Batteries, Natural Gas, or Gasoline (using "Climate Case" Electric Generation Mix)

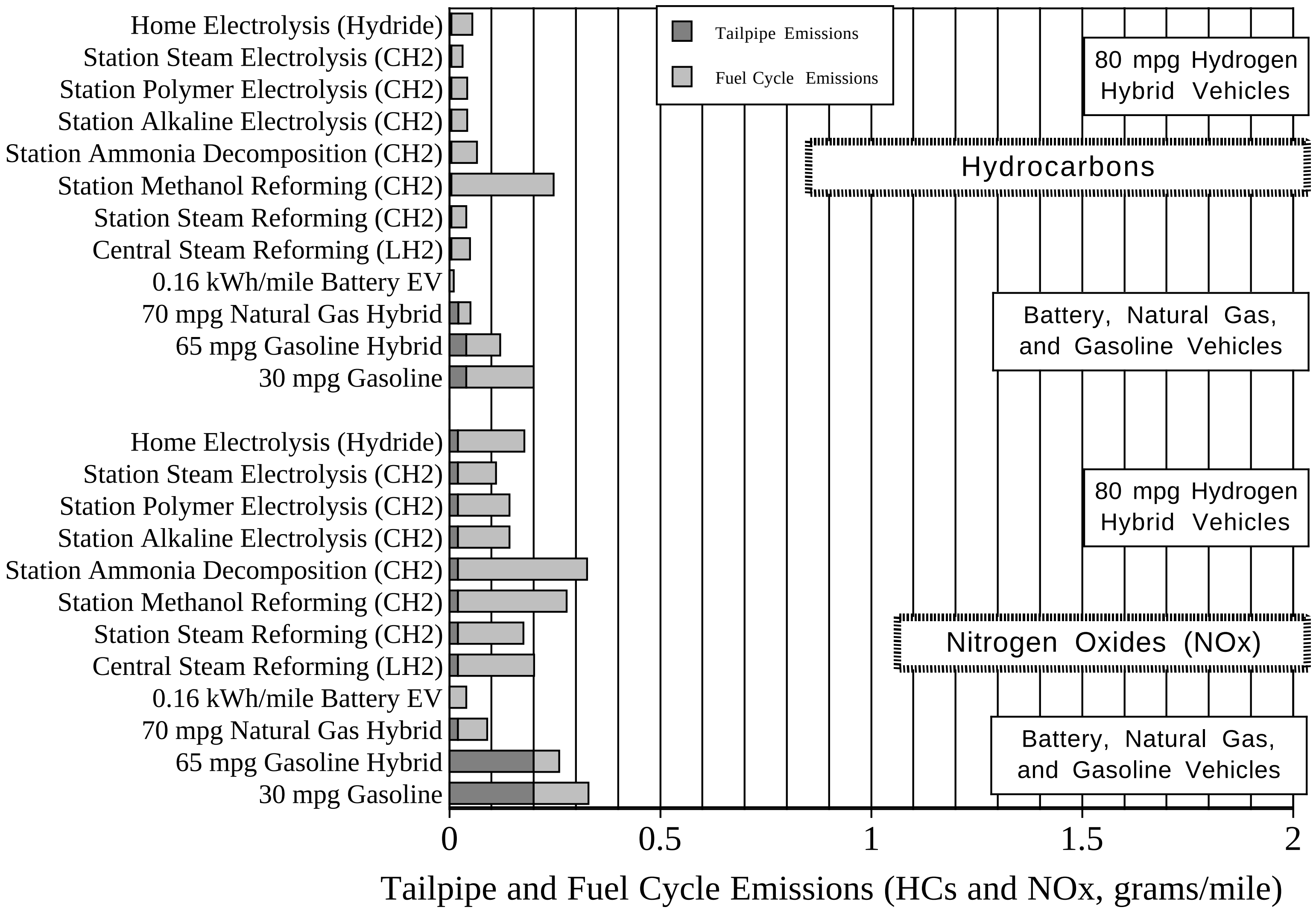

Figure 16(a–d). Fuel-cycle and tailpipe emissions of hydrocarbons and NOx are shown for the five vehicles and seven hydrogen pathways in Fig. 15 under the three electricity-mix scenarios of Fig. 14 in 2005 and 2035. Emissions improve markedly with technical advancements and changes in electricity-generation mix. Figure 16(a) shows emissions under the "reference" scenario in 2005. Figure 16(b–d) shows emissions under "reference," "market," and "climate" scenarios in 2035. Initially, NOx emissions, mostly from coal-based electricity, are sharply higher for hydrogen HEVs than for gasoline or natural-gas HEVs or for BPEVs. Hydrogen vehicles do have hydrocarbon emission reduction advantages, but overall hydrocarbon emissions are small. By 2035, however, NOx emissions are reduced sharply in all scenarios, and most hydrogen pathways achieve levels comparable to or better than ULEV gasoline vehicles. However, to reach NOx emissions levels as low as a natural-gas HEV, hydrogen vehicles require high-efficiency steam electrolysis and an electricity mix that relies largely (70%) on non-fossil generation.

Figure 17. U.S. Passenger Car Transportation Demand Scenario (2005-2050): Alternative Fuel Market Penetration and Oil Import Displacement

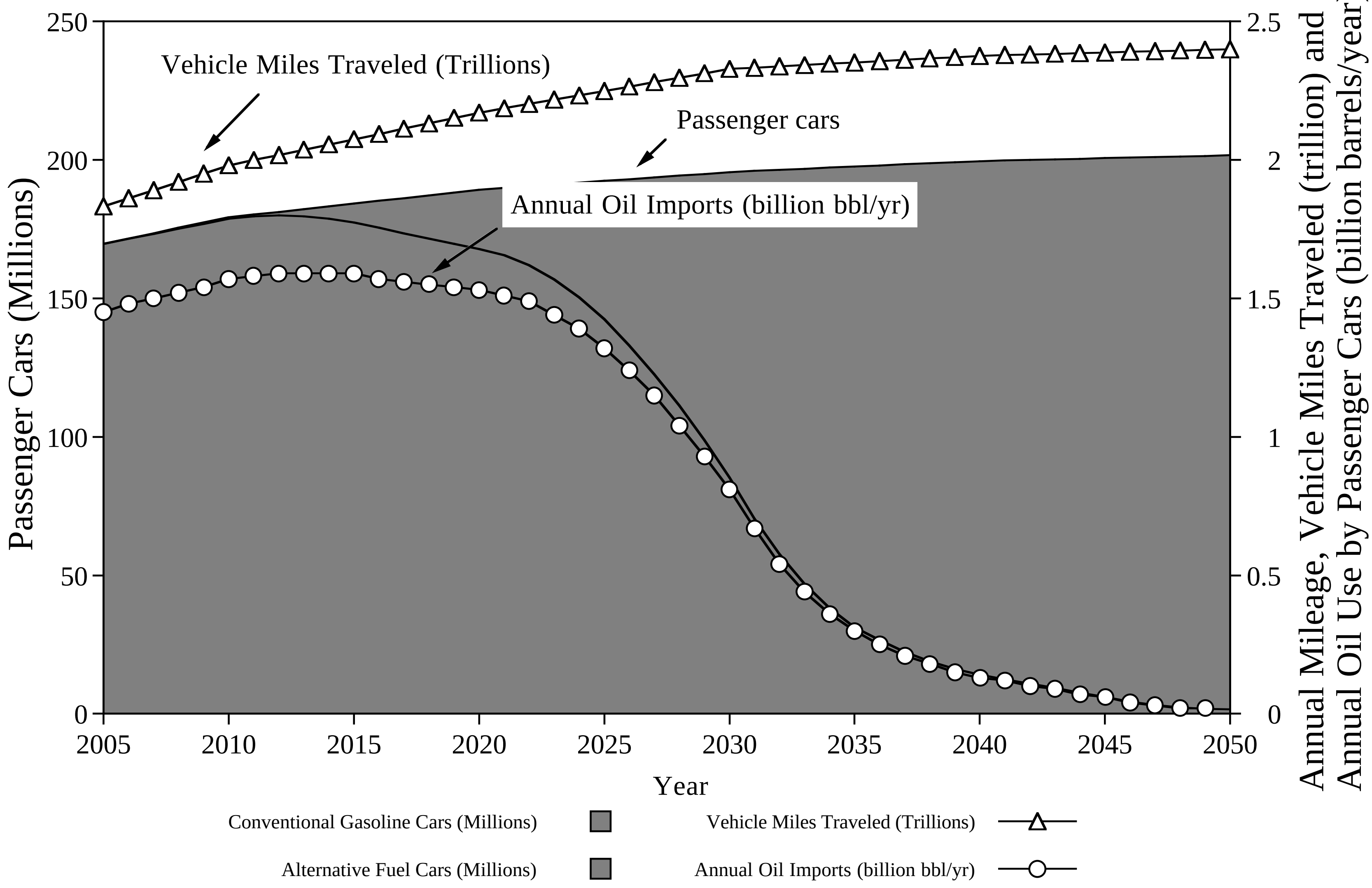

Figure 17. This figure sketches a scenario for converting the fleet from conventional 30-mpg gasoline vehicles to advanced vehicles (i.e., HEVs and BPEVs). This scenario is used to estimate the overall impacts of a transition from conventional gasoline vehicles to a variety of alternatives. Between 2005 and 2050, the U.S. passenger car fleet is expected to increase from 170 million to 200 million vehicles (left axis). Assuming vehicles are driven more as well, increasing from 10,000 to 12,000 miles/year, annual vehicle miles traveled will grow from 1.9 to 2.4 trillion/year by 2050 (right axis). As the figure indicates, to sharply reduce oil imports (also right axis) by 2025–2030 will require introducing alternative-fuel vehicles by at least two decades earlier (e.g., 2005) and dramatically increasing the number of alternative-fuel vehicles thereafter.

Figure 18(a). Carbon Dioxide Emissions Estimates for U.S. Cars (2005-2050)

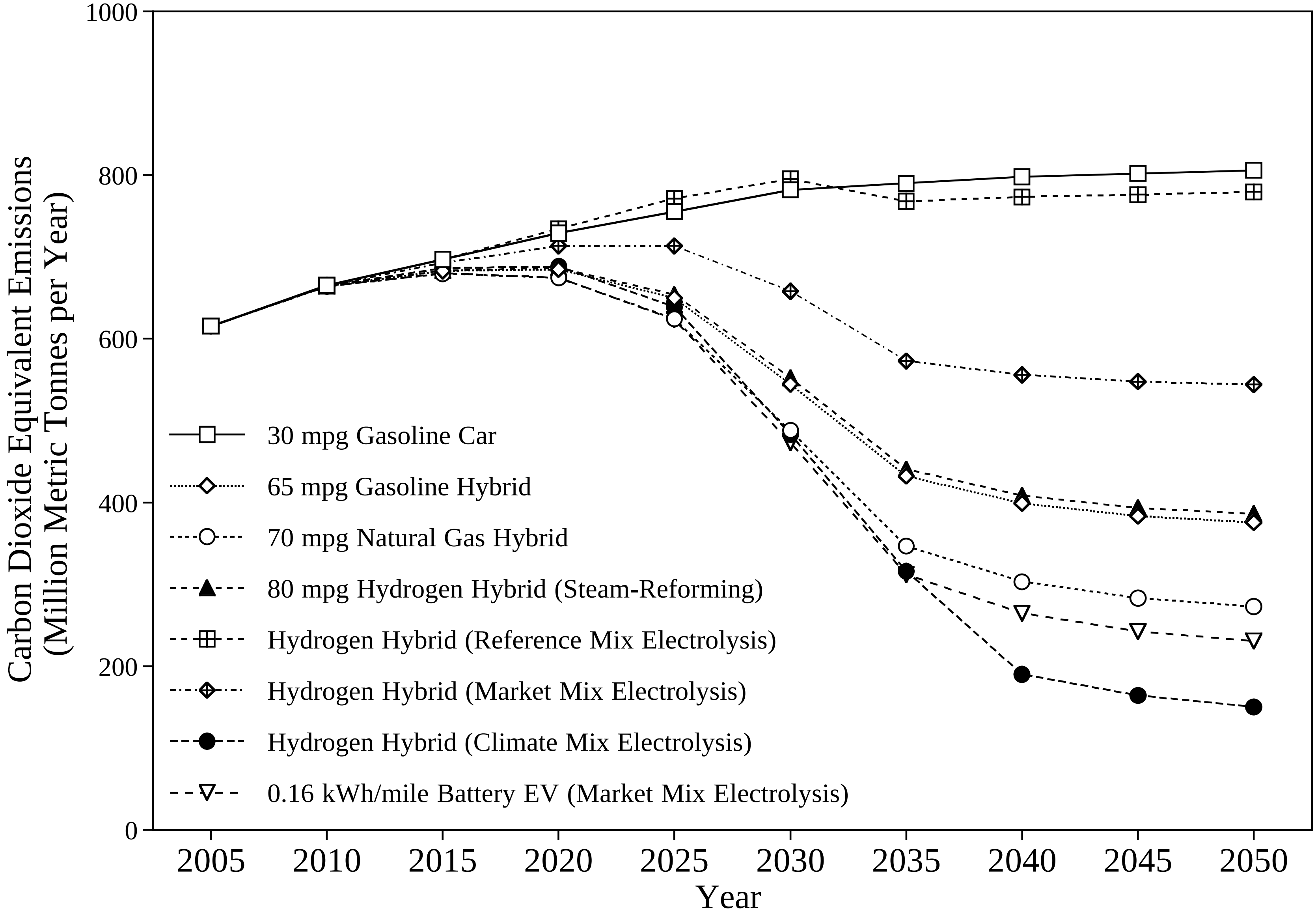

Figure 18(b). Nitrogen Oxide (NOx) Emissions Estimates for U.S. Cars (2005-2050)

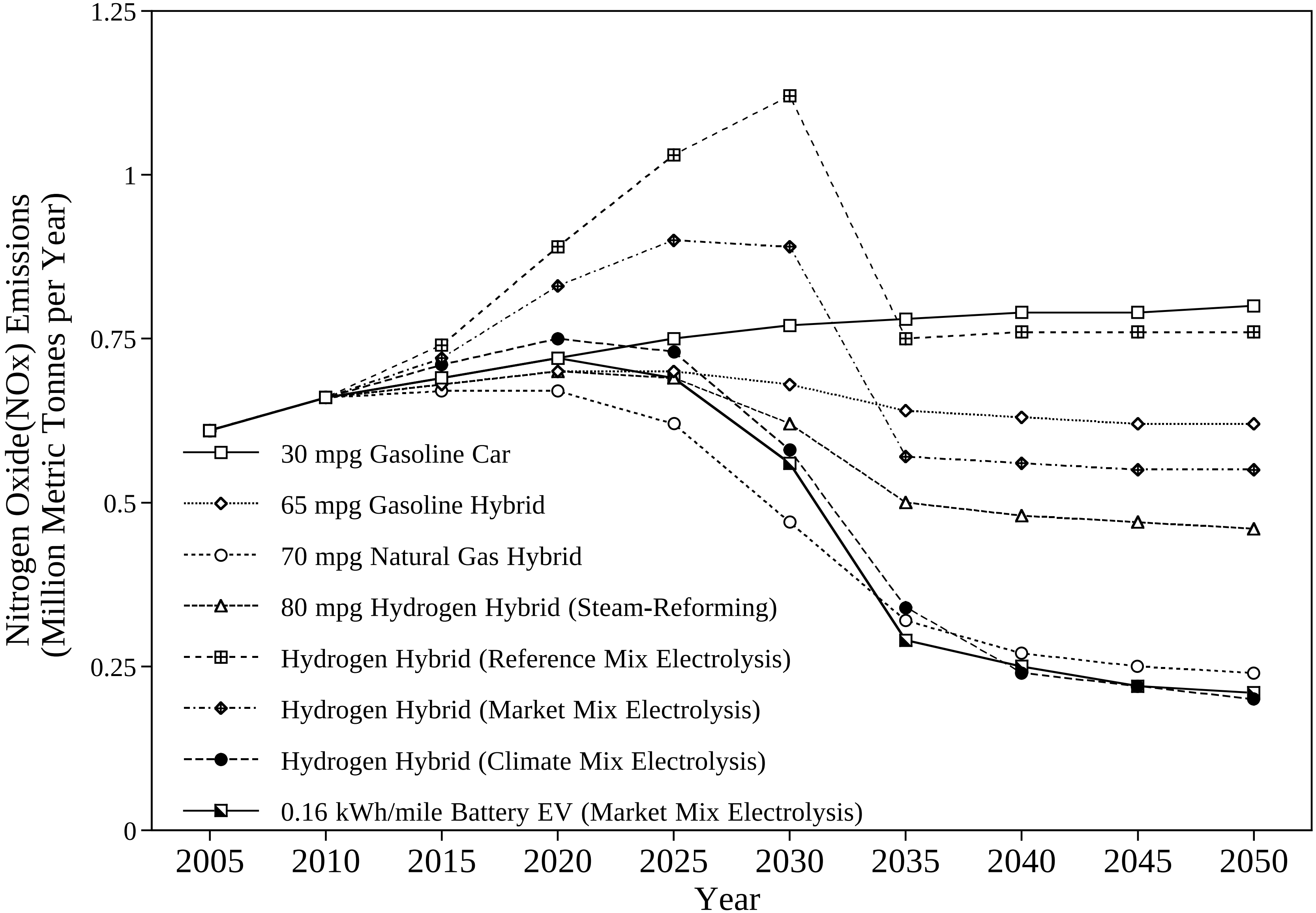

Figure 18(c). Hydrocarbon Emissions Estimates for U.S. Cars (2005-2050)

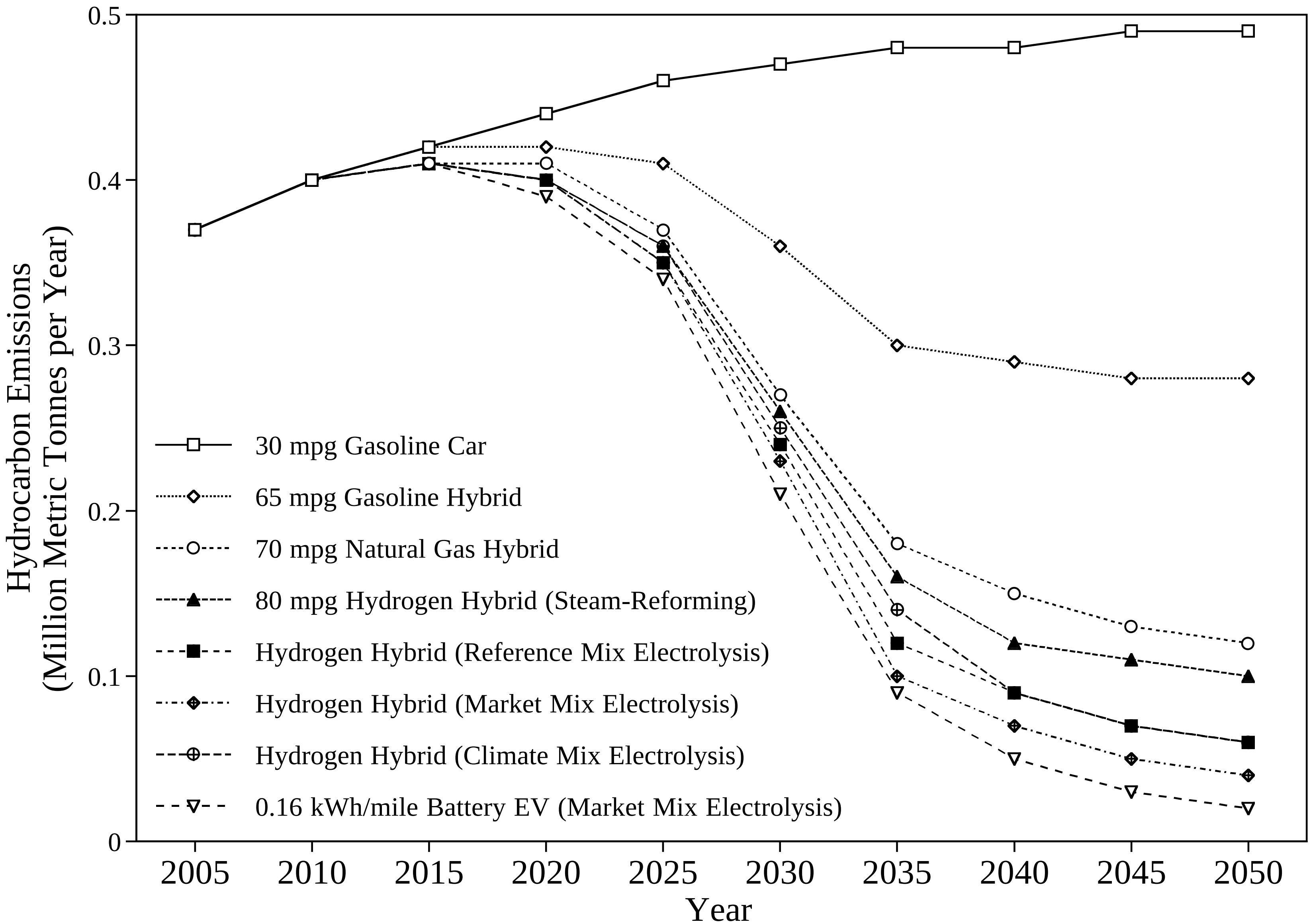

Figure 18(d). Carbon Monoxide (CO) Emissions Estimates for U.S. Cars (2005-2050)

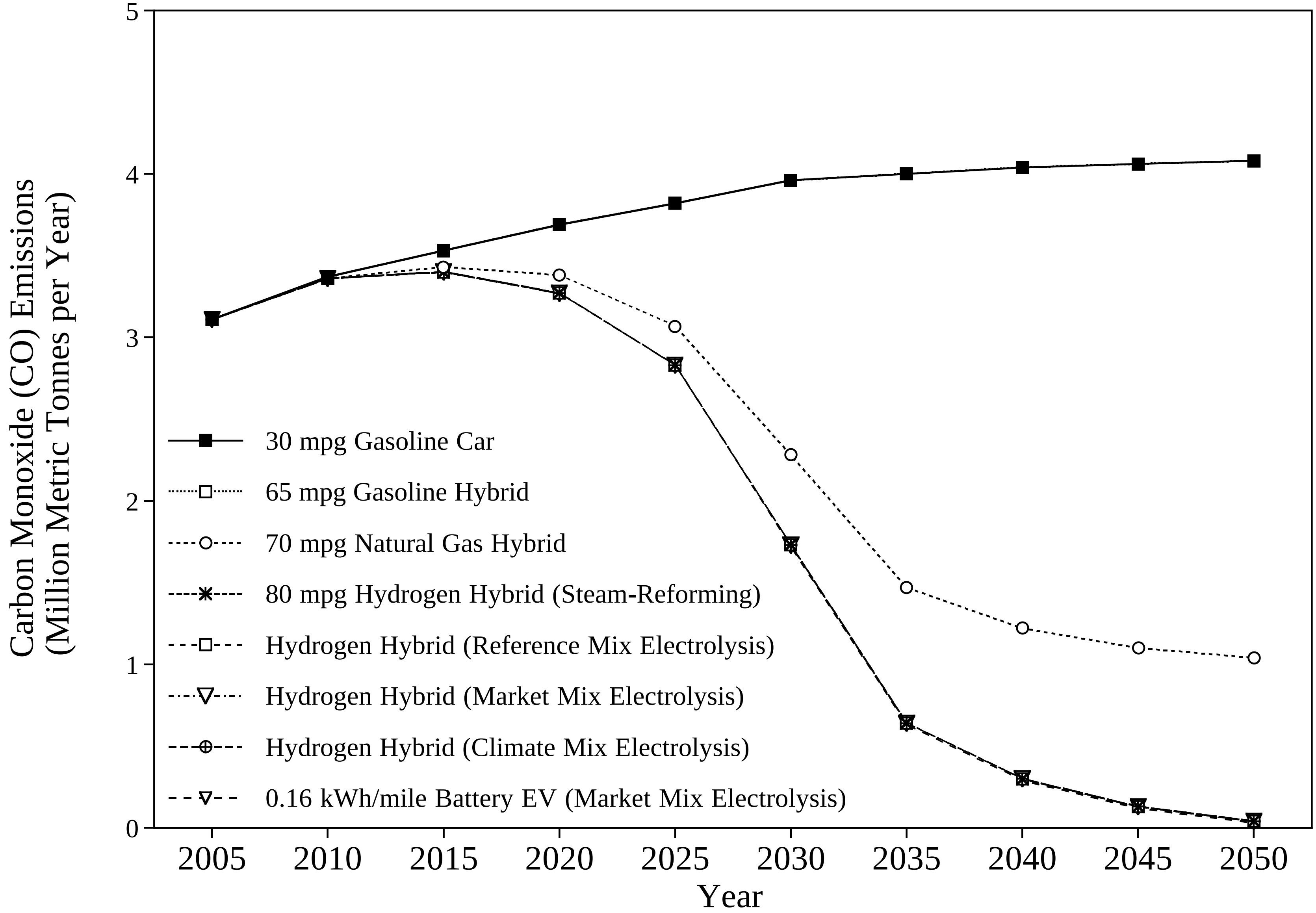

Figure 18(a-d). Annual CO_2, NOx, HC, and CO emissions for U.S. Passenger Car Fleet (2005-2050). Using the full-fuel-cycle vehicle emissions in Fig. 15 and 16 and the passenger car fleet size and use assumptions shown in Fig. 17, the total emissions from fueling U.S. passenger cars has been estimated under eight scenarios to demonstrate the emission impacts of continuing to use conventional gasoline vehicles or of a transition to a number of alternative vehicles, fuels, electricity mixes, and hydrogen production pathways. Figure 18(a) shows that hydrogen vehicles will require electrolysis under the "climate" electricity mix to provide the greatest reduction in CO_2 emissions. If hydrogen fuel is electrolyzed under more fossil-intensive mixes (on average), then greater emission reduction can be achieved by every other fuel / vehicle combination. If hydrogen is produced at stations by steam-reforming natural gas, then hydrogen vehicles are comparable to gasoline HEVs. Figure 18(b) shows that, in the case of NOx emissions, hydrogen vehicles again require the largely non-fossil "climate" electricity mix to achieve emissions reduction comparable to natural-gas HEVs or BPEVs, although steam-reformed hydrogen can provide emission reductions over gasoline HEVs. Figure 18(c) shows that for hydrocarbon emissions hydrogen vehicles provide large and similar emission reduction benefits whether the fuel is made electrolytically or by steam-reforming. However, natural-gas HEVs approach the emissions levels of steam-reformed hydrogen cars, and BPEVs provide lower emissions than hydrogen vehicles. Figure 18(d) shows that for CO emissions hydrogen vehicles provide large emission reductions over gasoline, but natural gas can achieve 75% of these emissions reductions as well. Note that, in Fig. 18(d), all of the lines are superimposed on each other, except for the 30-mpg gasoline car and the 70-mpg natural-gas hybrid.

Figure 19(a). Cumulative Carbon Dioxide (CO_2) Emissions for U.S. Cars (2005-2050)

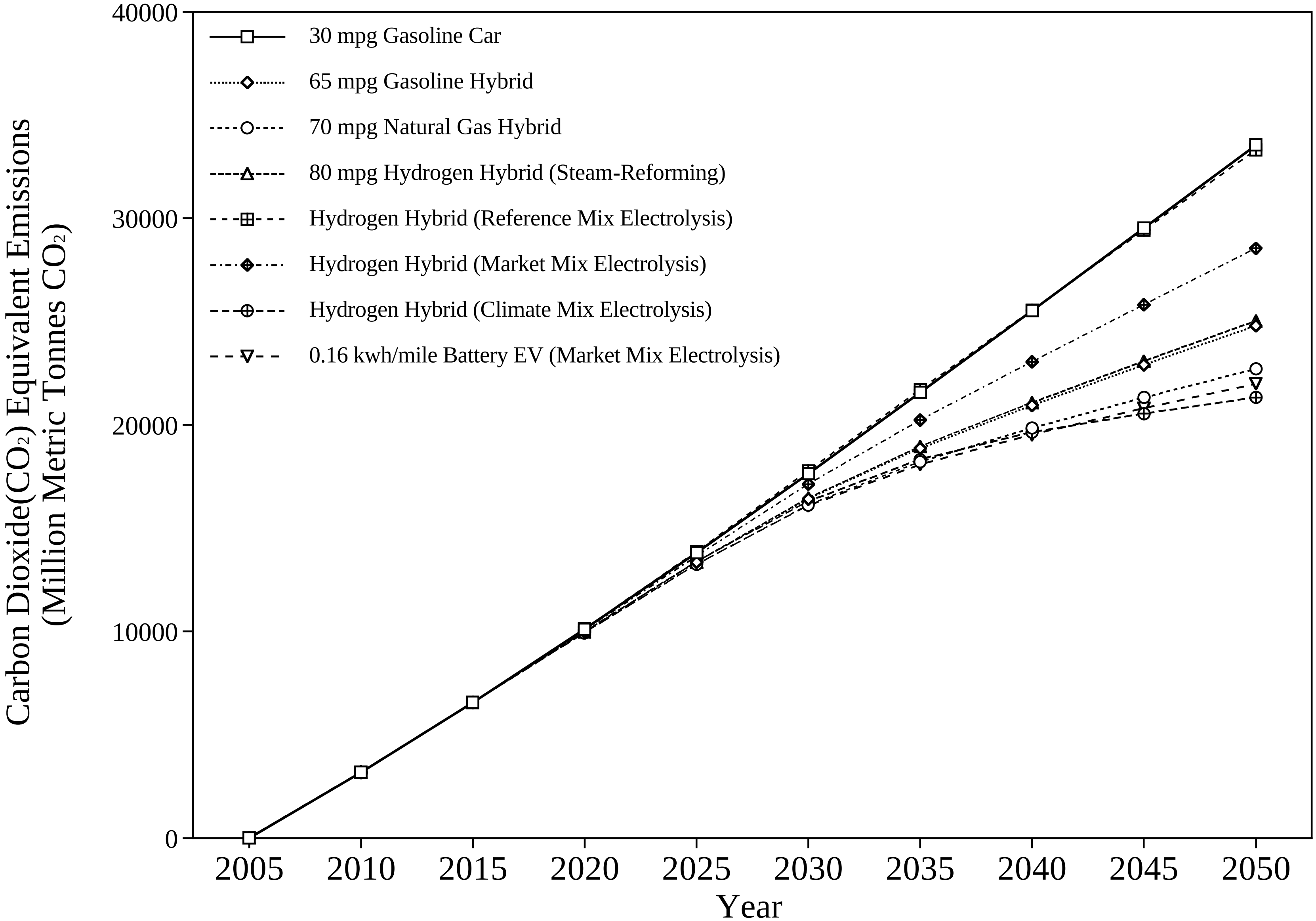

Figure 19(b). Cumulative Nitrogen Oxide (NOx) Emissions for U.S. Cars (2005-2050)

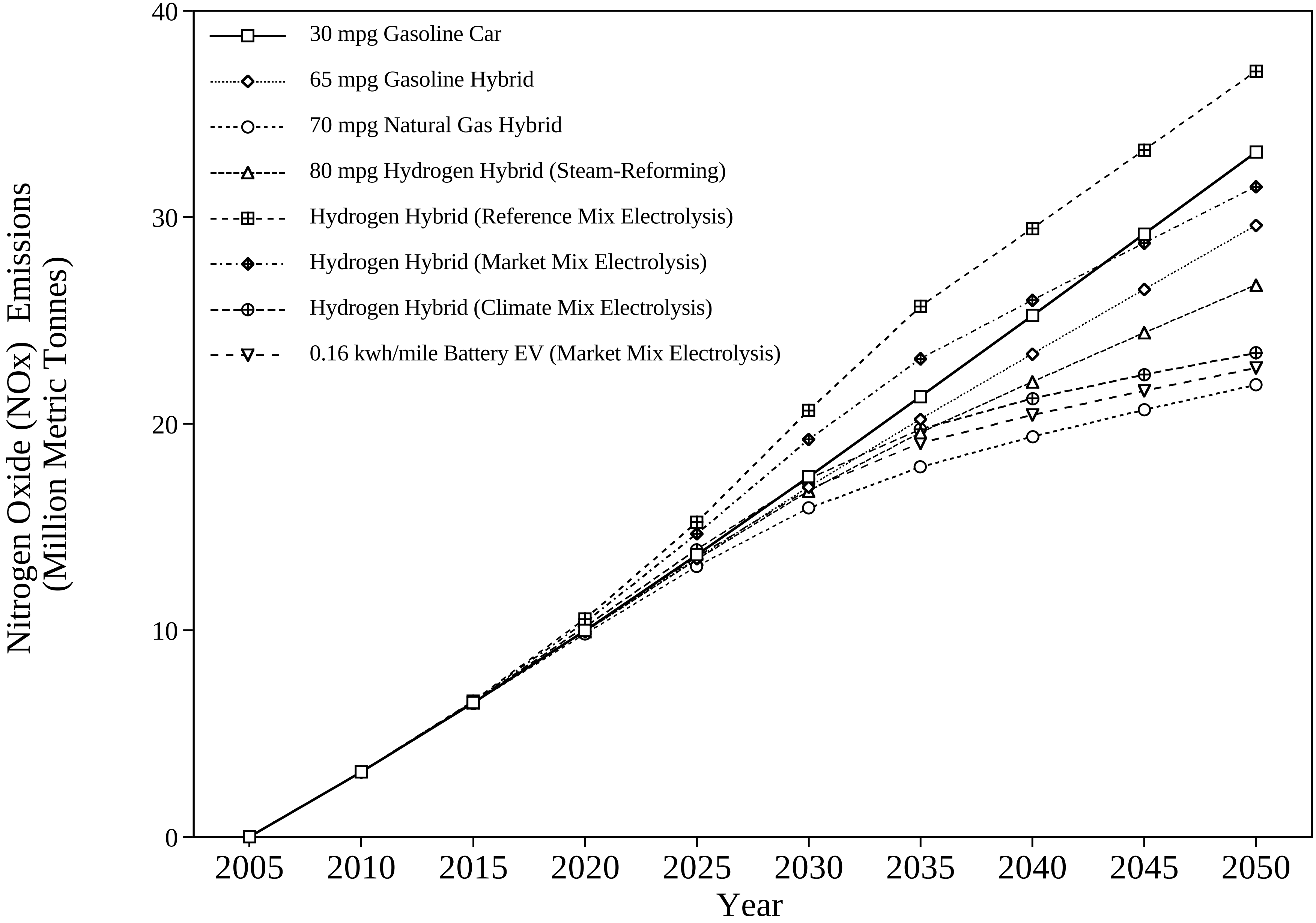

Figure 19(c). Cumulative Hydrocarbon Emissions for U.S. Cars (2005-2050)

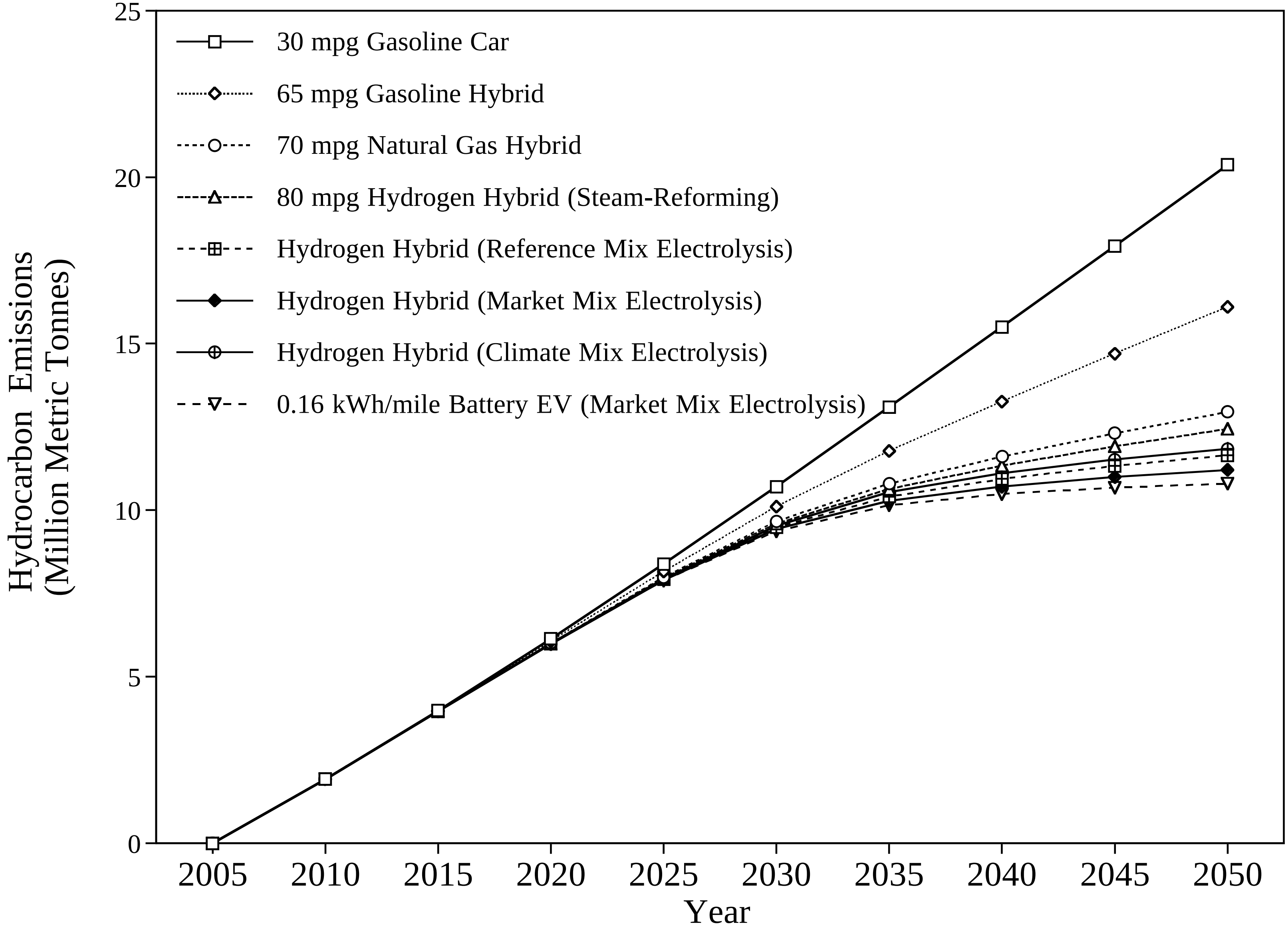

Figure 19(d). Cumulative Carbon Monoxide (CO) Emissions for U.S. Cars (2005-2050)

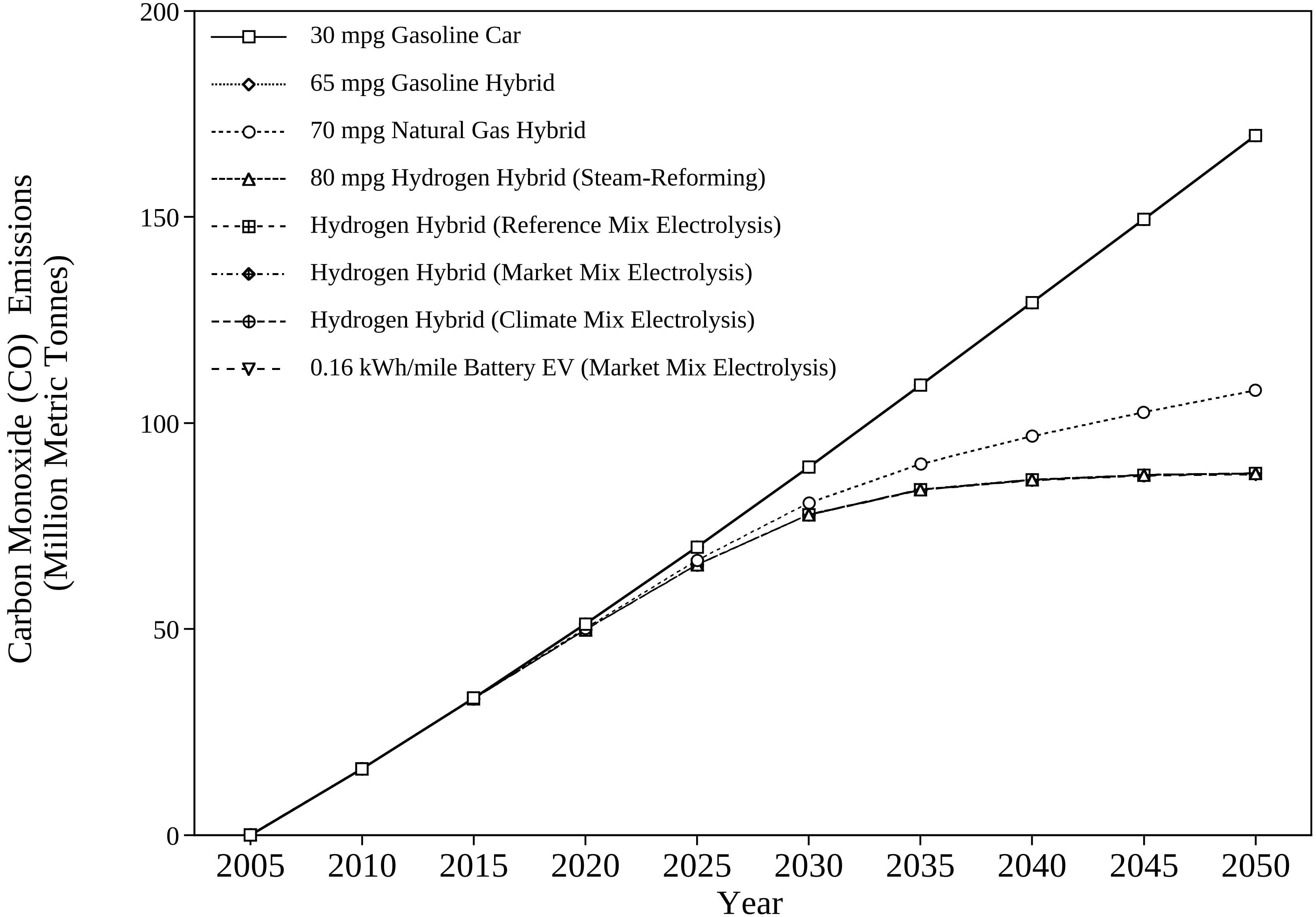

Figure 19 (a-d). Cumulative full-fuel-cycle emissions for U.S. passenger cars over the period 2005–2050 are shown for same eight scenarios presented in Fig. 18, based on the electricity mixes, emissions factors, and passenger car fleet assumptions of Fig. 14, 15–16 and 17, respectively. Figure 19(a) shows that emissions savings of roughly 15 billion tons of CO_2-equivalent greenhouse gases through 2050 are achievable by natural-gas HEVs, BPEVs, and electrolytic hydrogen vehicles under a largely non-fossil electric-generating mix (the "climate" mix). Steam-reformed hydrogen vehicles and 65-mpg gasoline HEVs achieve comparable emission reductions. Fossil- intensive electricity mixes limit and possibly eliminate emission reductions with electrolytic hydrogen vehicles over conventional 30-mpg gasoline cars. Figure 19(b) shows that, in the case of NOx emissions, roughly 12 million metric tons can be saved by 2050 by a transition from 30-mpg gasoline vehicles to natural-gas or hydrogen HEVs, using steam-reformed hydrogen or electrolytic hydrogen under the "climate" electric generation mix. Fossil (particularly coal) electric generation eliminates the potential emission savings of electrolytic hydrogen cars. Figure 19(c) shows that roughly 10 million metric tons of hydrocarbon emissions can be saved by a transition from 30-mpg gasoline vehicles to hydrogen or natural-gas HEVs or to BPEVs, relatively independent of changes in the electricity mix. Figure 19(d) shows that approximately 100 million metric tons of CO emissions can be eliminated by a transition from gasoline to hydrogen HEVs or BPEVs, but 80% of these savings can be achieved by natural-gas HEVs.

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